Sterile Neutrino Searches (an unfinished story)

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May 3, 2021

Seminar at Stony Brook University, Stony Brook, NY

Special thanks to P. Huber, Chao Zhang, and others.
White paper: 1204.5379
PDG: 2018 , 2020 review of neutrinos

Diwan, Galymov, Qian, Rubbia, https://www.annualreviews.org/doi/full/10.1146/annurev-nucl-102014-021939

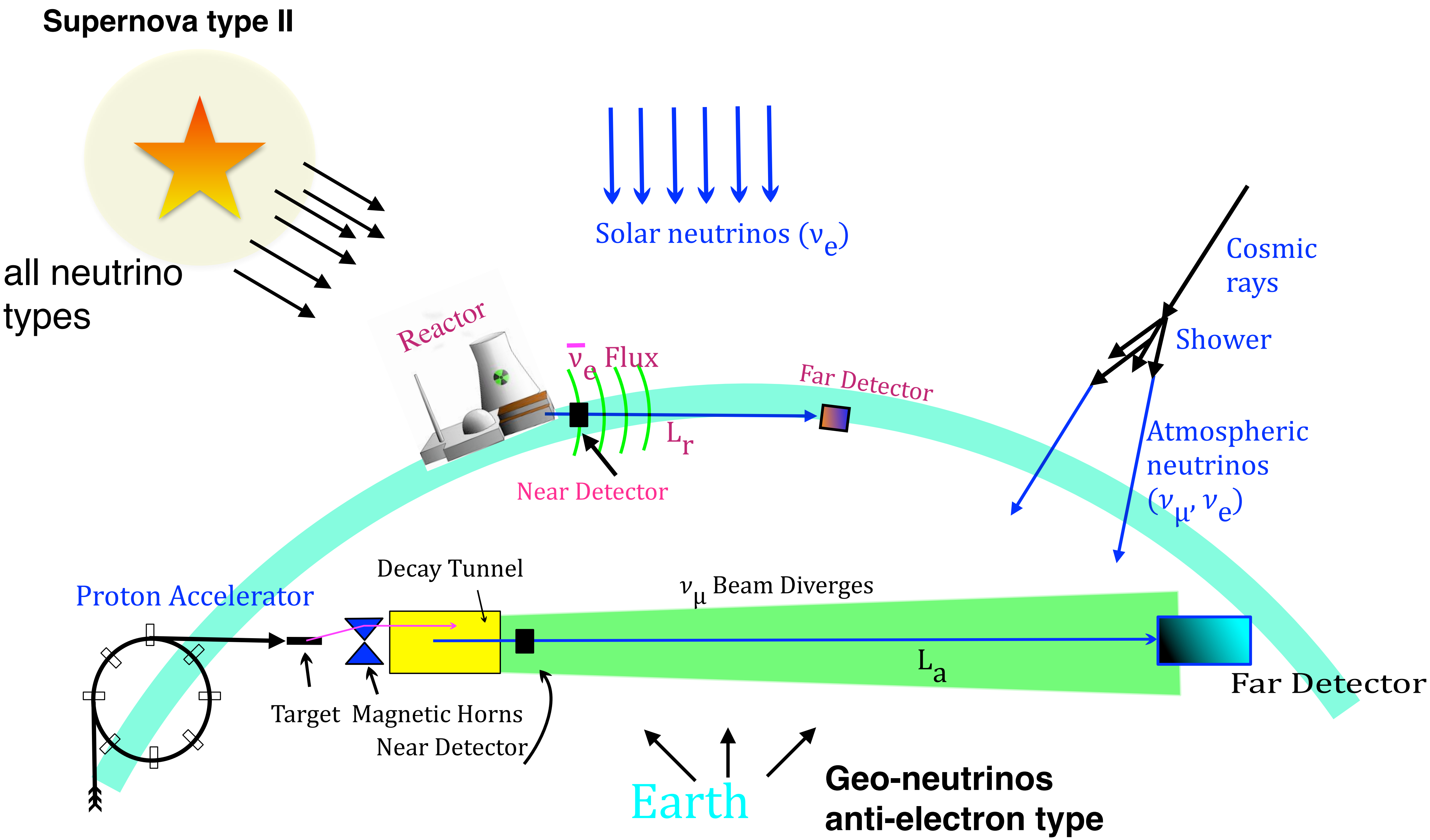
Something for fun: Diwan, Mcnulty-Walsh, https://kids.frontiersin.org/article/10.3389/frym.2020.00045

BROOKHAVEN NATIONAL LABORATORY

Outline

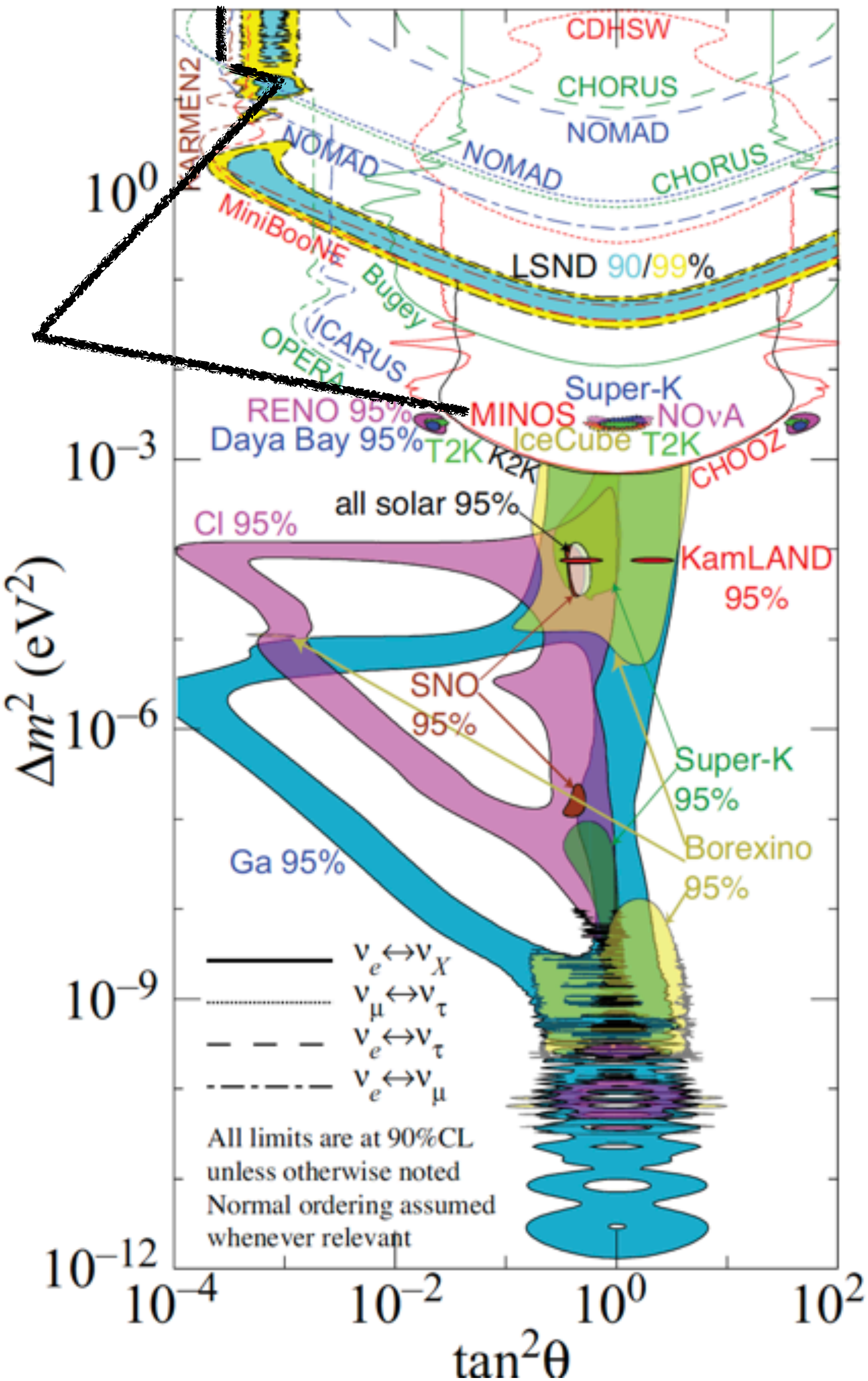
- ***Generalities***
  - ***"Sterile Neutrinos are a Sterile Idea" - Maurice Goldhaber (2000)***
  - ***The search for fundamental neutral states is extremely well motivated because of the known mystery of dark matter and the unknown nature of the neutrino.***
- ***Big picture: 3 neutrinos and phase space for a 4th light state: brief review of neutrino sources and what they have taught us.***
- ***Direct evidence for a sterile state.***
- ***Evidence from oscillations***
  - ***Reactor oscillations - RAA (reactor antineutrino anomaly)***
  - ***Accelerator based oscillations***
- ***Experimental Outlook***

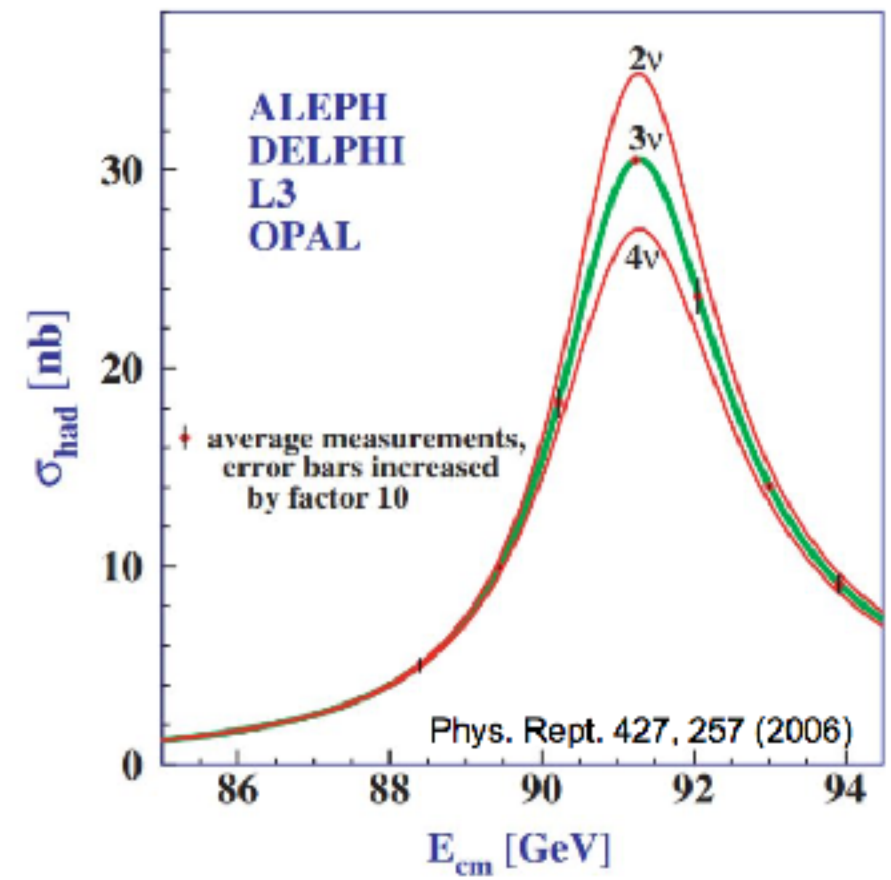
Neutrino Sources



Natural and manmade sources of led us to understand the ν properties.
Annual Rev. 66, 2016.
All information on neutrino masses and mixings has come from oscillation of neutrinos from these sources.

MINOS+DB+B





The electroweak and the most compelling neutrino oscillation data is consistent with 3 active neutrinos that have small masses and large mixings.

But sterile neutrinos that do not have electroweak coupling are allowed at any mass scale.

- **Very Heavy right-handed (~10^{12} GeV) considered to be natural partners of light left-handed neutrinos**
- **Light (<10 eV) could be observable through mixing.**
- **keV scale could form dark matter. observable through decays.**

Large mixing of ν_s with active neutrinos is excluded across ~10 orders of mag. For <1eV ν_s is effectively excluded 1204.5379

State of 3-neutrinos

NuFIT 5.0 (2020)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

NuFIT 5.0 (2020)

$$|U|^{\text{w/o SK-atm}}_{3\sigma} = \begin{pmatrix} 0.801 \to 0.845 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.631 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

This analysis assumes unitarity

$$\theta_{23} \sim \pi/4,\ \theta_{12} \sim \pi/6,\ \theta_{13} \sim \pi/20$$

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 \approx 1$$

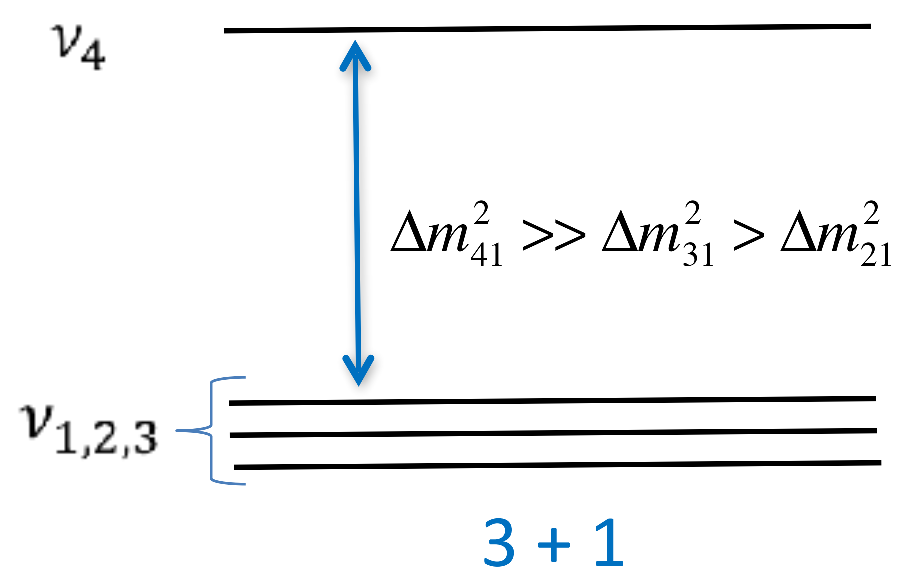
The current constraint is quite weak and even weaker on the other rows. Large mixing with sterile is quite possible.

Example analysis without unitarity on the first row of the matrix using reactor and solar data: 1308.5700

**SK atmospheric data makes the NO preferred.*

3(active)+1(sterile) formalism

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



- ***The 3 active neutrinos have much lower masses and so this is an effective 2 neutrino system with a new $\Delta m^2 > 1\ eV^2$***
- ***Oscillations will be at much smaller L/E ~1 km/GeV or 1 m/MeV where atmospheric and solar oscillations can be ignored.***

Appearance:

$$P(\nu_\alpha \to \nu_\beta) \cong 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

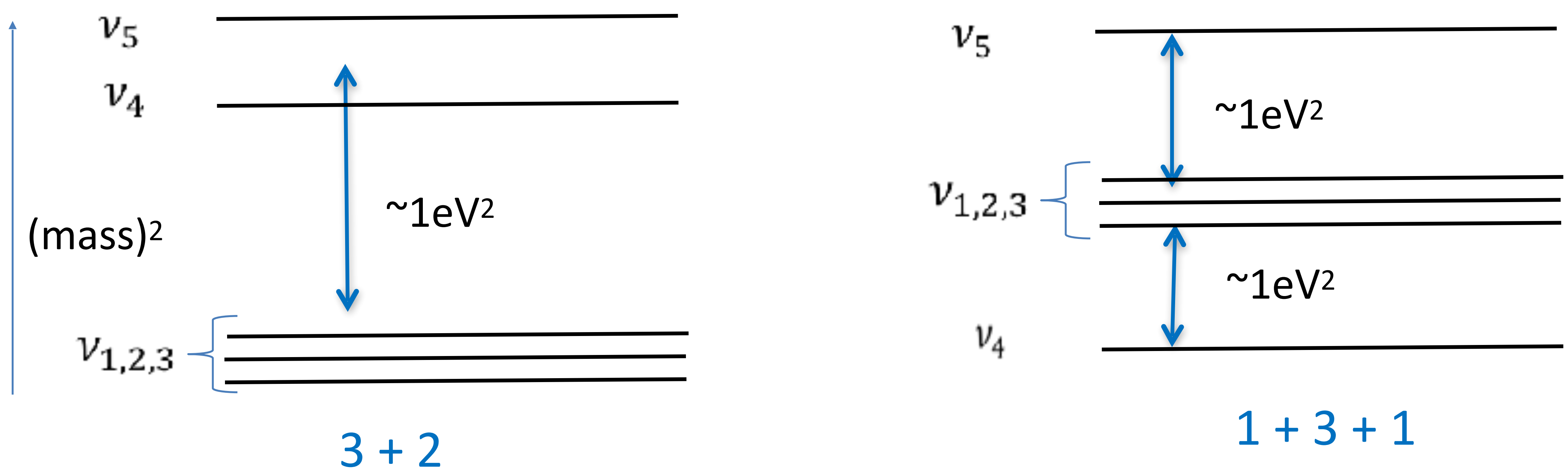
$$\cong sin^2 2\theta_{\alpha\beta}\ sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

Disappearance:

$$P(\nu_\alpha \to \nu_\alpha) \cong 1 - 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

$$\cong 1 - sin^2 2\theta_{\alpha\alpha}\ sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

More than 1 sterile neutrino ?



CPT: $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha) \Rightarrow \; P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$

Disappearance in neutrinos and antineutrinos must be the same.

CP-violation: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

But this can happen only if there are $\geq 2\ \Delta\text{m}^2$ participating, and so there cannot be CP violation in a 3(active)+1(sterile) system which is effectively 2-ν

Addition of more than 1 sterile neutrino can introduce CP Violation allowing different appearance results for neutrinos and anti-neutrinos.
A 3 (active)+2(sterile) system is effectively a 3-ν system if the sterile masses are much larger than the active ones.

Muon and electron neutrino oscillations in 3+1

For any two flavors there is a triplet of observable oscillations.

$$P(\nu_\mu \to \nu_e) \cong 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{\mu e} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_{\not{\mu}}) \cong 4|U_{\mu 4}|^2 (1-|U_{\mu 4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{\mu\mu} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_e \to \nu_{\not{e}}) \cong 4|U_{e4}|^2 (1-|U_{e4}|^2) \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right) = \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right)$$

$$P(\nu_\alpha \to \nu_{\not{\alpha}}) \approx P(\nu_\alpha \to \nu_s)$$

For small mixing

$$\sin^2 2\theta_{\mu e} = \frac{1}{4} \sin^2 2\theta_{\mu\mu} \sin^2 2\theta_{ee} \quad \text{and} \quad \theta_{\mu\mu} \sim \theta_{24} \quad \theta_{ee} \sim \theta_{14}$$

This gives an upper bound after averaging over the oscillations

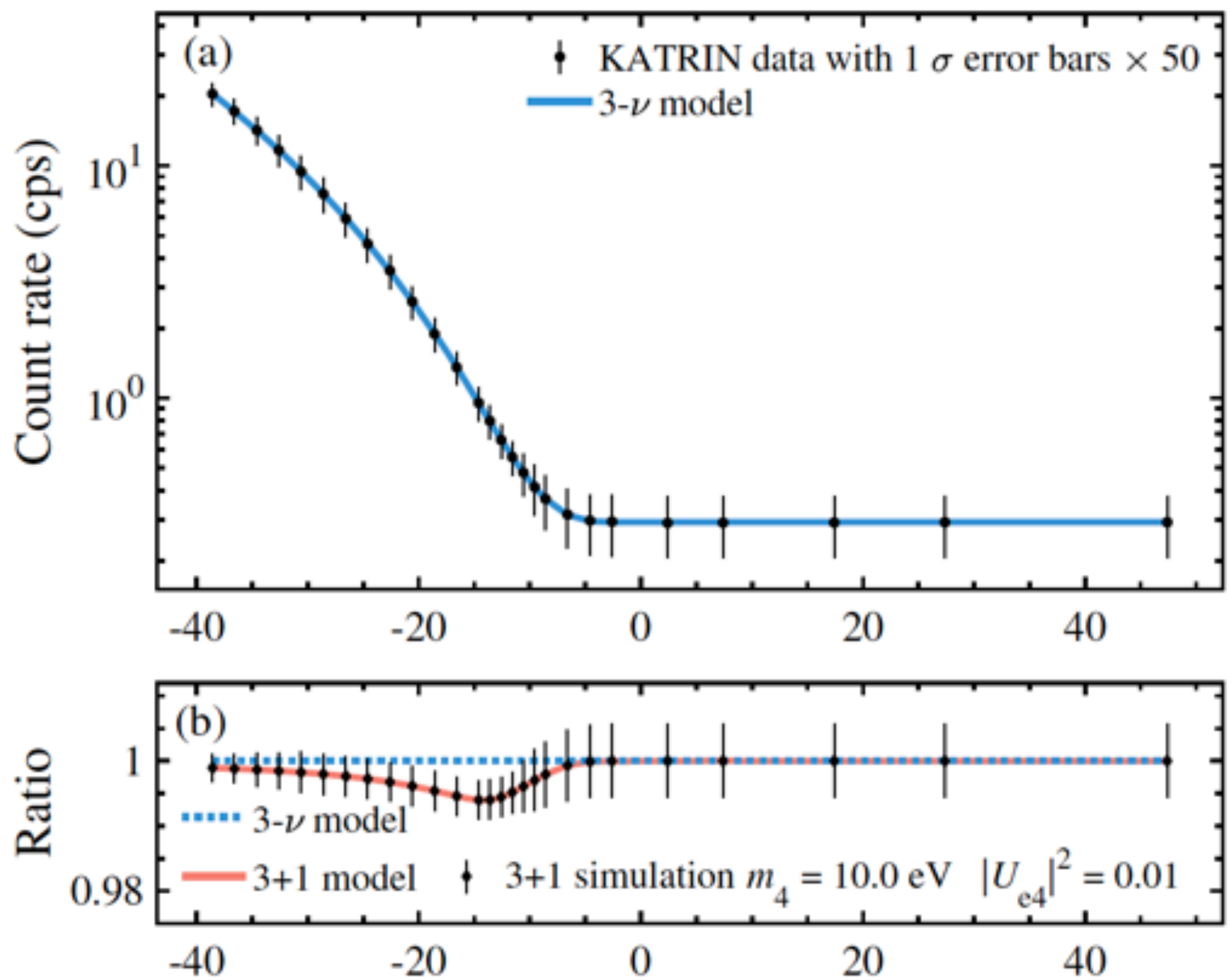
$$P(\nu_\mu \to \nu_e) \leq \frac{1}{2} P(\nu_\mu \to \nu_{\not{\mu}}) \times P(\nu_e \to \nu_{\not{e}})$$

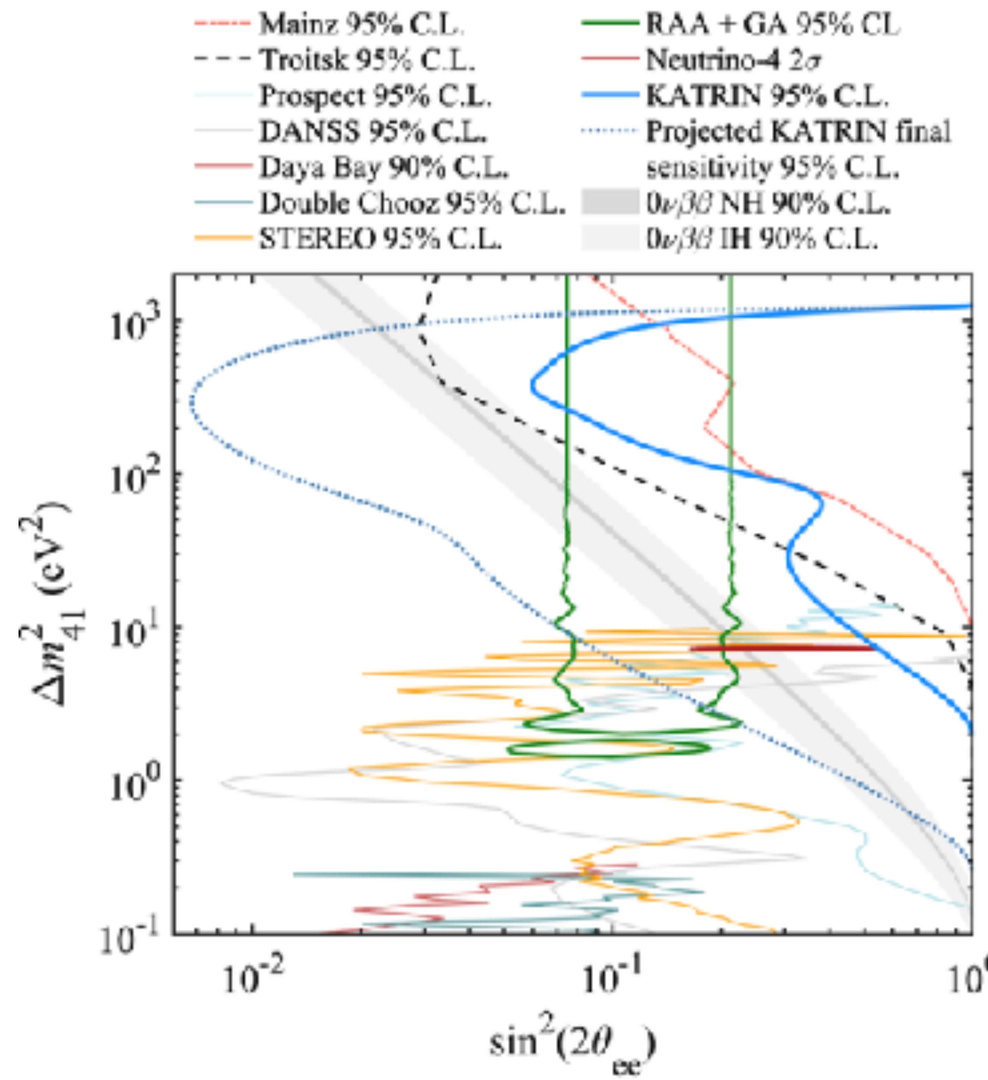
Although derived for 3+1 this should be independent of number of sterile neutrinos.

Regardless, the triplet of oscillations must be consistent if appearance is found.

Each of the disappearances separately is allowed without appearance.

Direct detection of sterile neutrinos from decays.





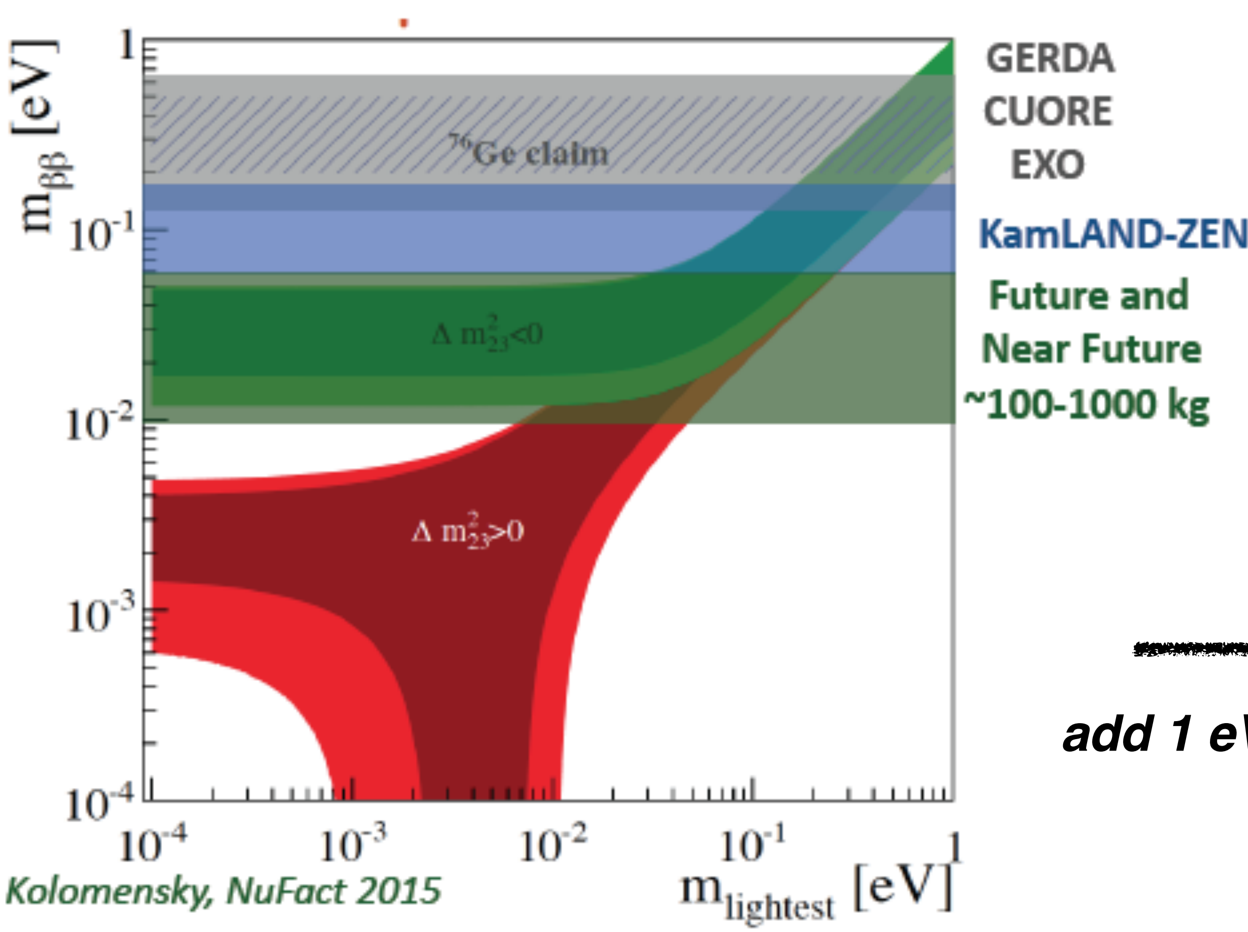
$$R_\beta(E, m_\nu, m_4) = (1 - |U_{e4}|^2) R_\beta(E, m_\nu) + |U_{e4}|^2 R_\beta(E, m_4)$$

Katrin result on sterile neutrinos for $m_{\nu 4}^2 < 1000 eV^2$

PHYSICAL REVIEW LETTERS 126, 091803 (2021)

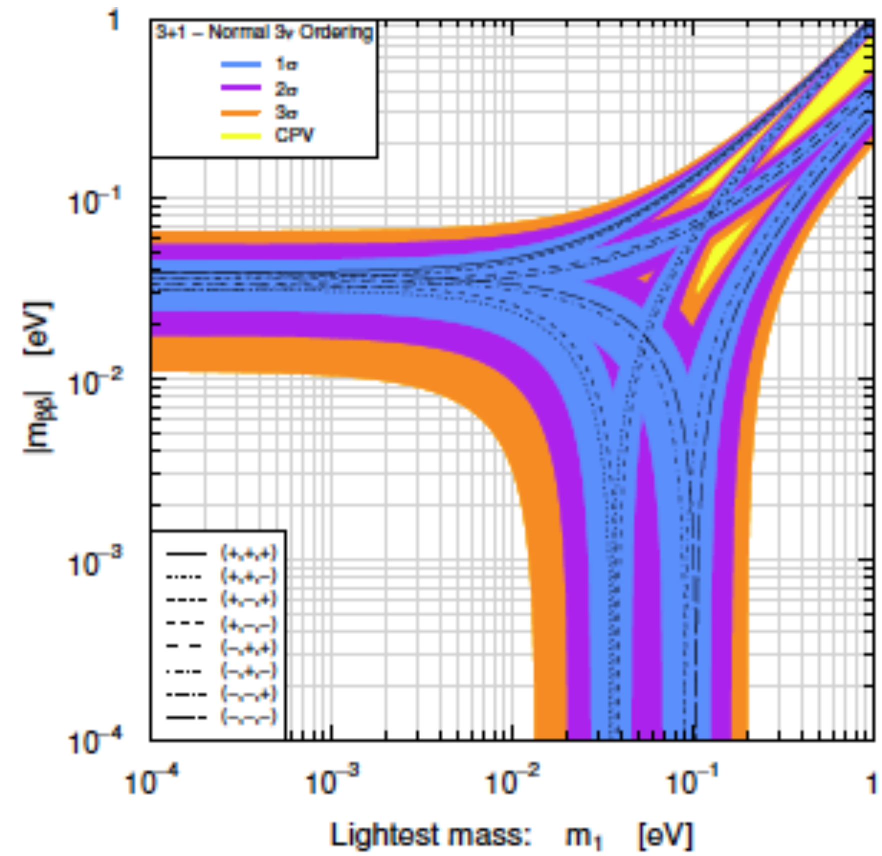
- ***Also see Bryman, Schrock, PRD.100.053006 for MeV to GeV neutrinos.***

Neutrino less double beta decay with sterile



Y. Kolomensky, NuFact 2015

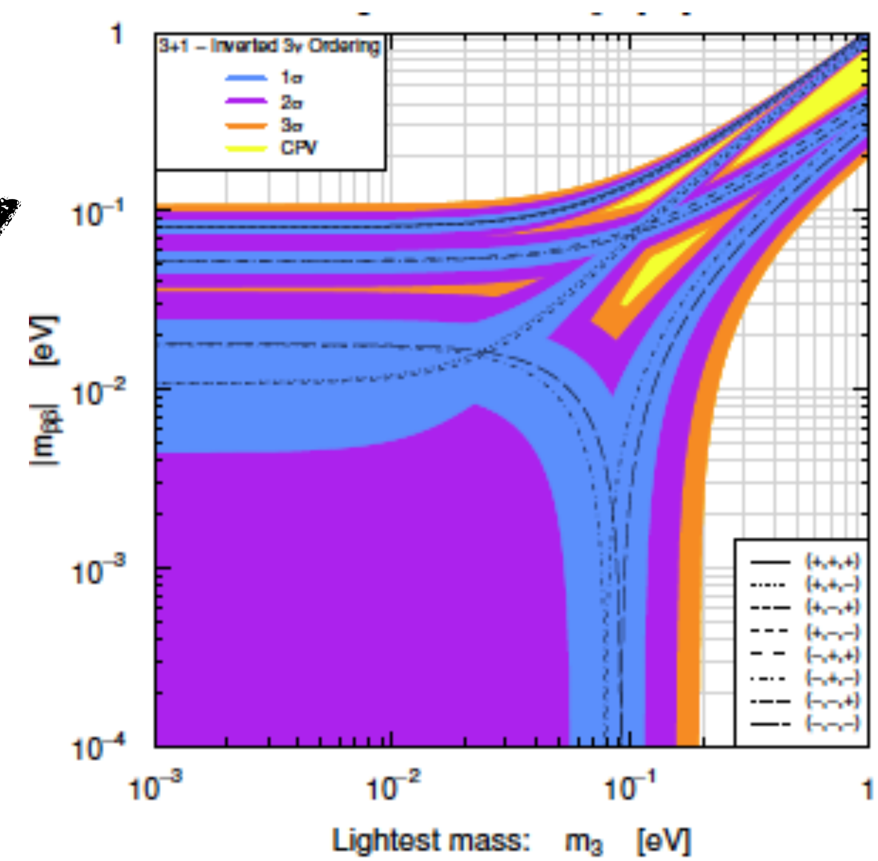
add 1 eV sterile



$$\left|m_{\beta\beta}\right| = \left|\sum \left|U_{ej}\right|^2 m_j e^{i\alpha_j}\right|$$

inverted 3ν

$$T_{1/2} \propto 1/\left|m_{\beta\beta}\right|^2$$



If there is a 1 eV sterile neutrino with mixing according to global fit then NLDBD could be accessible over a larger range of values. 1507.08204

Some history pre-LSND

- ***Many accelerator oscillations experiments were carried out >1eV^2 because the large laboratories had L/E=1 km /1 GeV.***
- ***Motivation from astrophysics in the past to find a ~1eV state.***
- ***Almost all experiments struggled with backgrounds to the electron neutrino signal.***
- ***“A value of a candidate depends on the background” — Maurice Goldhaber***

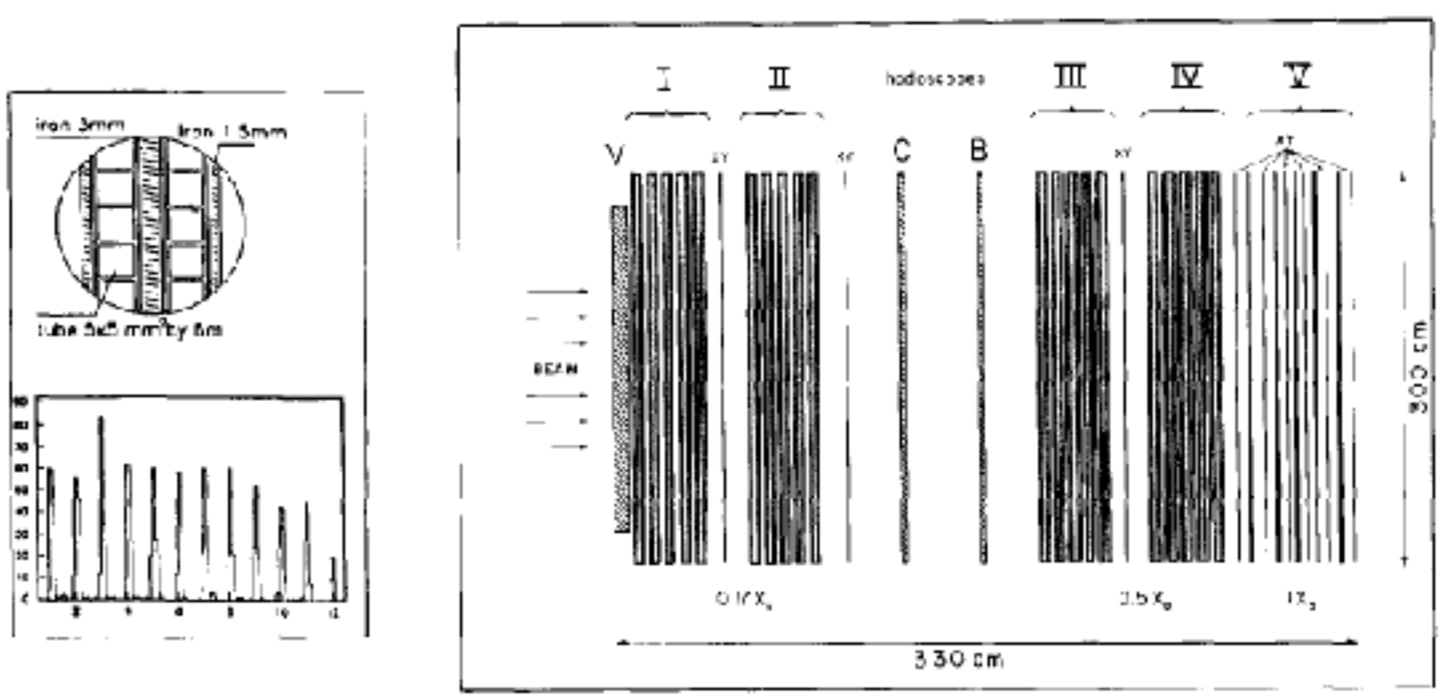
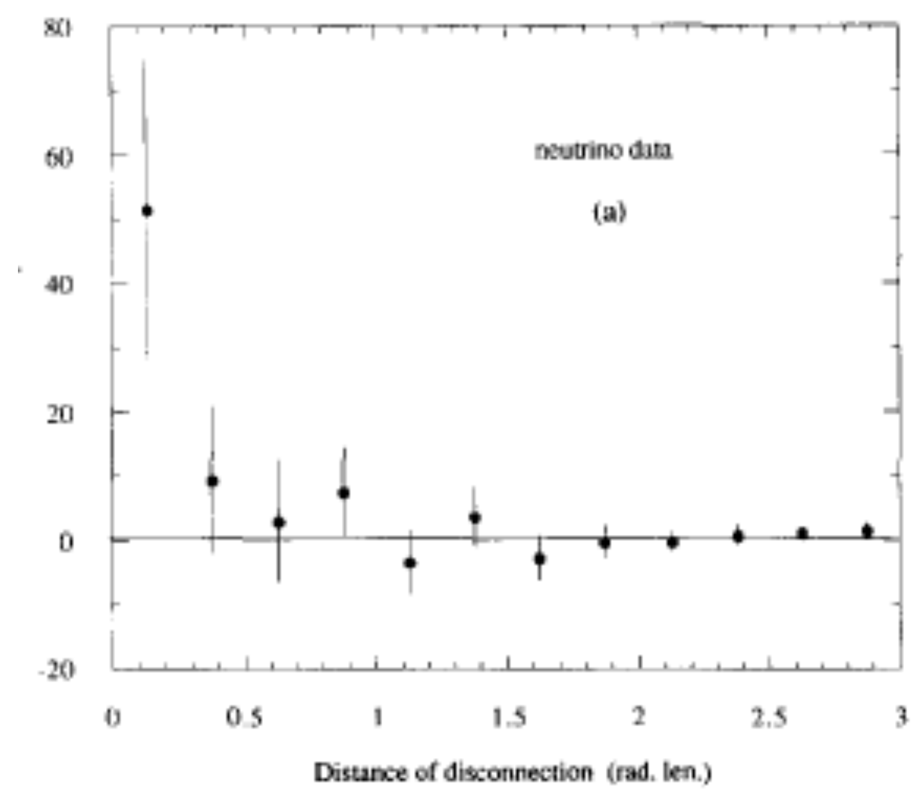


Fig. 1. The detector. The inset shows details of the flash chamber and the beam burst structure as measured by the experiment (horizontal scale gives time in units of 224 ns).



Example: AGS-816 had 1 view readout to measure e/gamma showers.

ref: CERN-EP-89-128,

Search for Neutrino Oscillations P. Astier et al.. Jan 1989. 18 pp. Published in Phys.Lett. B220 (1989) 646

A signal was found using the gap between vertex and shower.

also see summary by Aronson, Murtagh: bnl-42369

Status in 1993

Status 2015

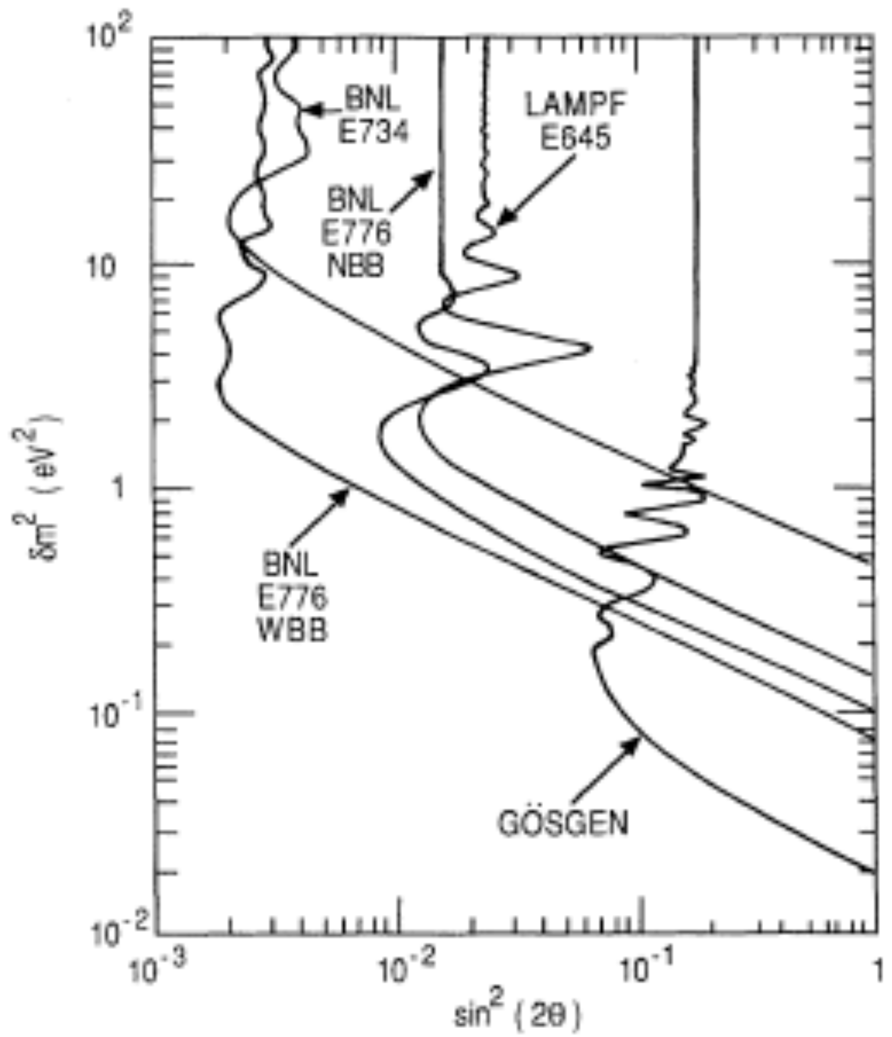


FIG. 31. Comparison of selected flavor-changing neutrino oscillation limits. The figure combines limits from appearance experiments with neutrinos and antineutrinos with the best limits from reactor disappearance experiments. The limits are comparable under the simplest assumptions of two-flavor neutrino mixing. See (Blumenfeld *et al.*) Ref. [10], BNL 776 NNB (narrow band beam); (Borokovsky *et al.*) Ref. [10], BNL WBB (wide-band beam); (Ahrens *et al.*) Ref. [9], BNL E734; and (Zacek, *et al.*), Ref. [6], Gösgen.

S.J. Freedman et al. (E645 collaboration), PRD 47 no. 3, 811 (1993)

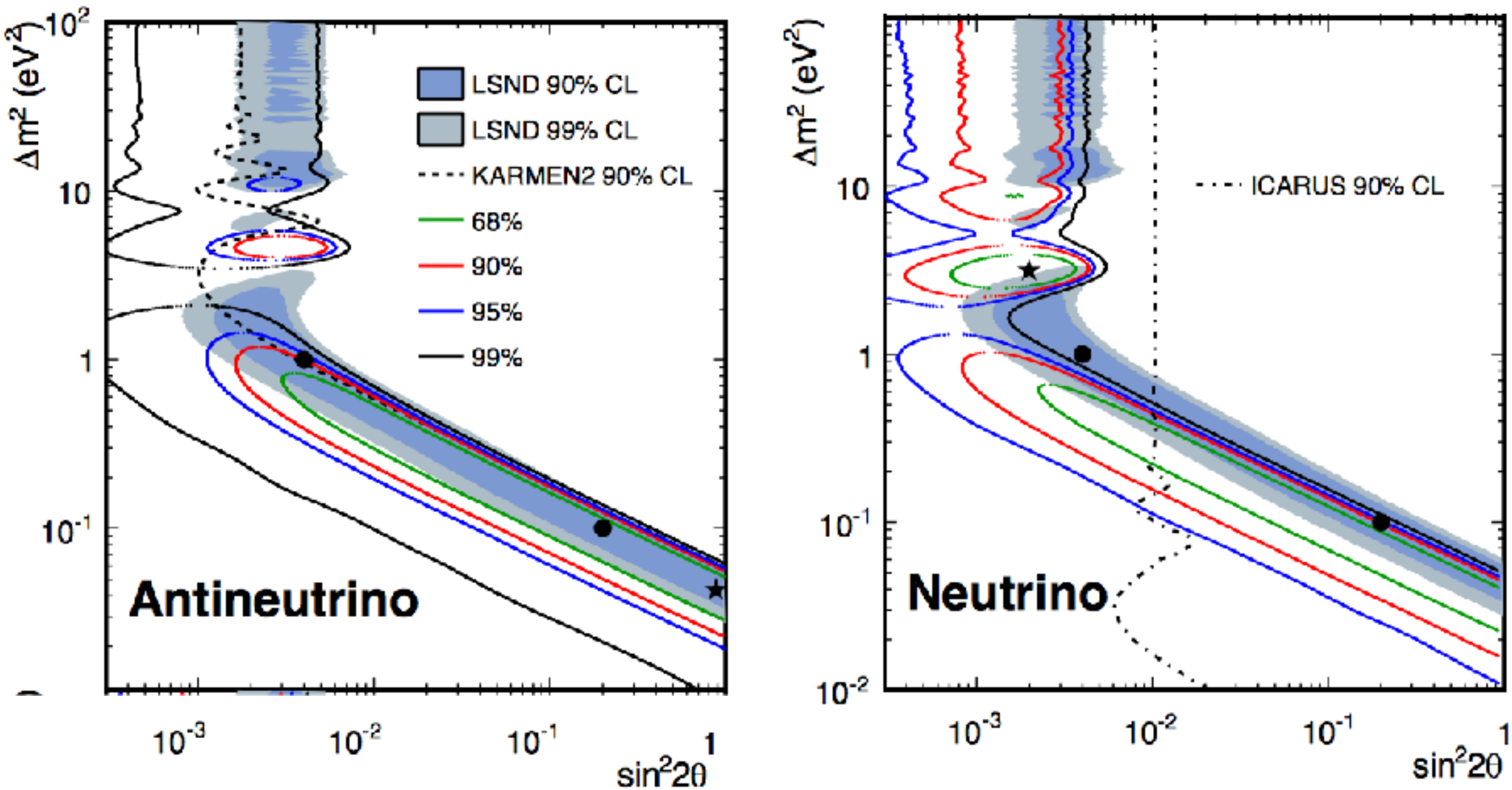
- LSND Excess
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ (3.8σ)
- MiniBoone Excess
  - $\bar{\nu}_\mu \to \bar{\nu}_e$ (2.8σ)
  - $\nu_\mu \to \nu_e$ (3.4σ)
  - combined (3.8σ)
- Reactor anomaly
  - $\bar{\nu}_\mu \to \bar{\nu}_s$ (3.0σ)
- Gallium anomaly
  - $\nu_e \to \nu_s$ (2.7σ)

An eV scale sterile neutrino would fit all of these, except for MiniBoone neutrino excess.

This status has again changed rapidly with disappearance results from accelerator and reactors.

MiniBooNE/LSND Results Comparison

Phys. Rev. Lett.110, 161801 (2013)



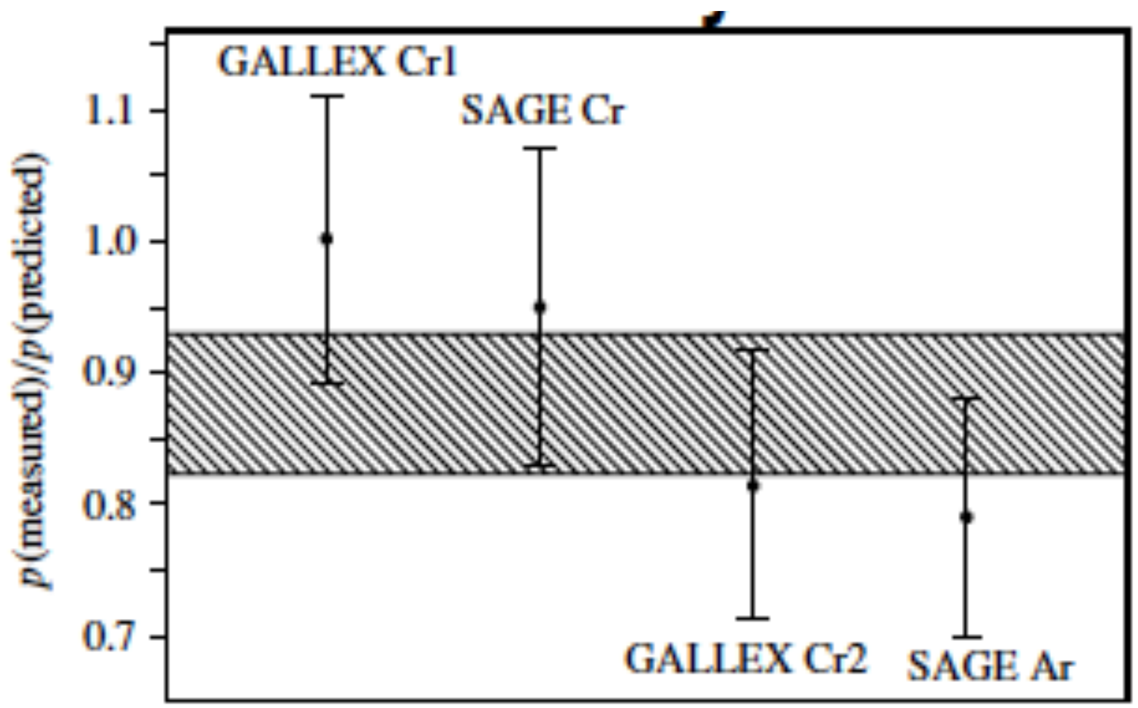
- $\bar{\nu}$ **electron excess is 2.8 sigma in 200-475MeV. Outside LSND allowed region.**
- ν **electron excess is 3.4 sigma from 200-475MeV and also incompatible with LSND and** $\bar{\nu}$ **data.**

The Gallium Anomaly: $\nu_e \rightarrow \nu_s$

The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources (^{51}Cr and ^{37}Ar) to calibrate the detector. There were 4 experiments.

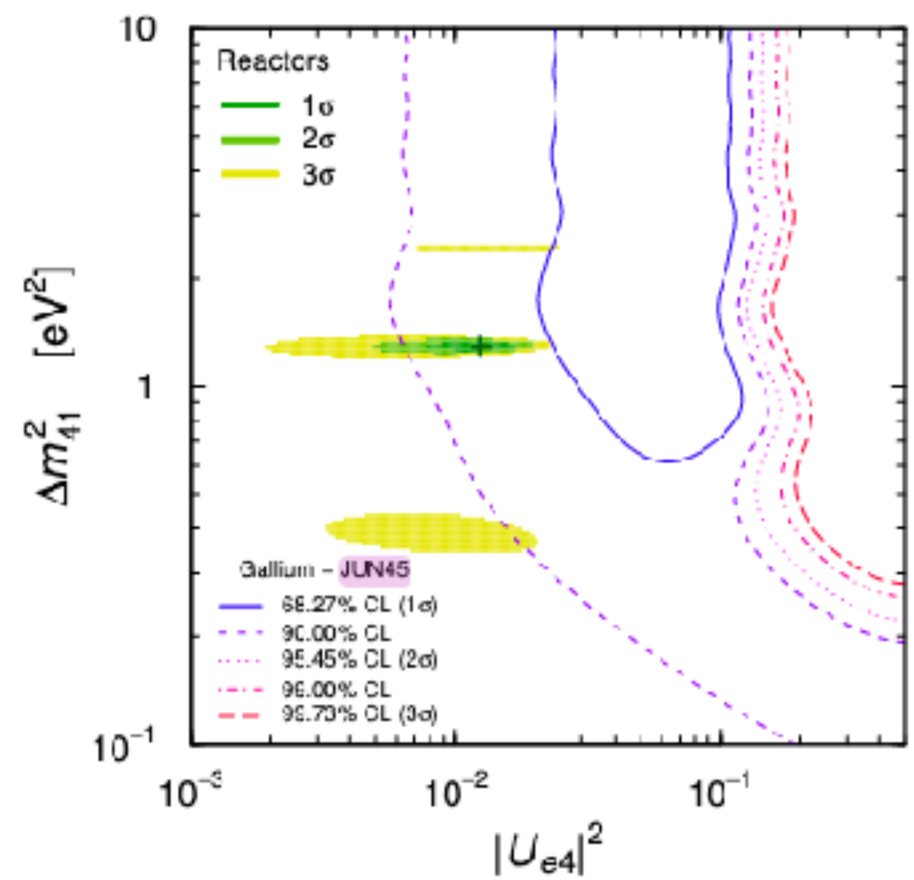
$$e^- + {}^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + \nu_e\,,$$

$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e\,,$$



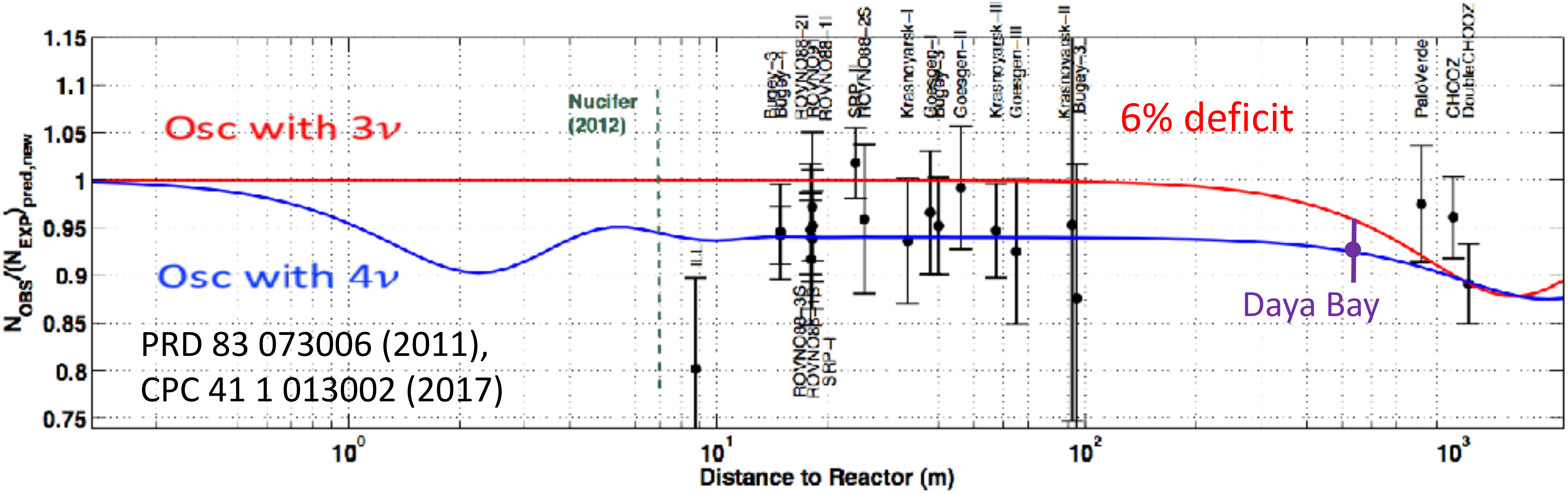
No oscillation is disfavored by 2.3-3 sigma depending on the cross section model used.
New experiment: BEST(Russia)

PRD. 83 073006 (2001)

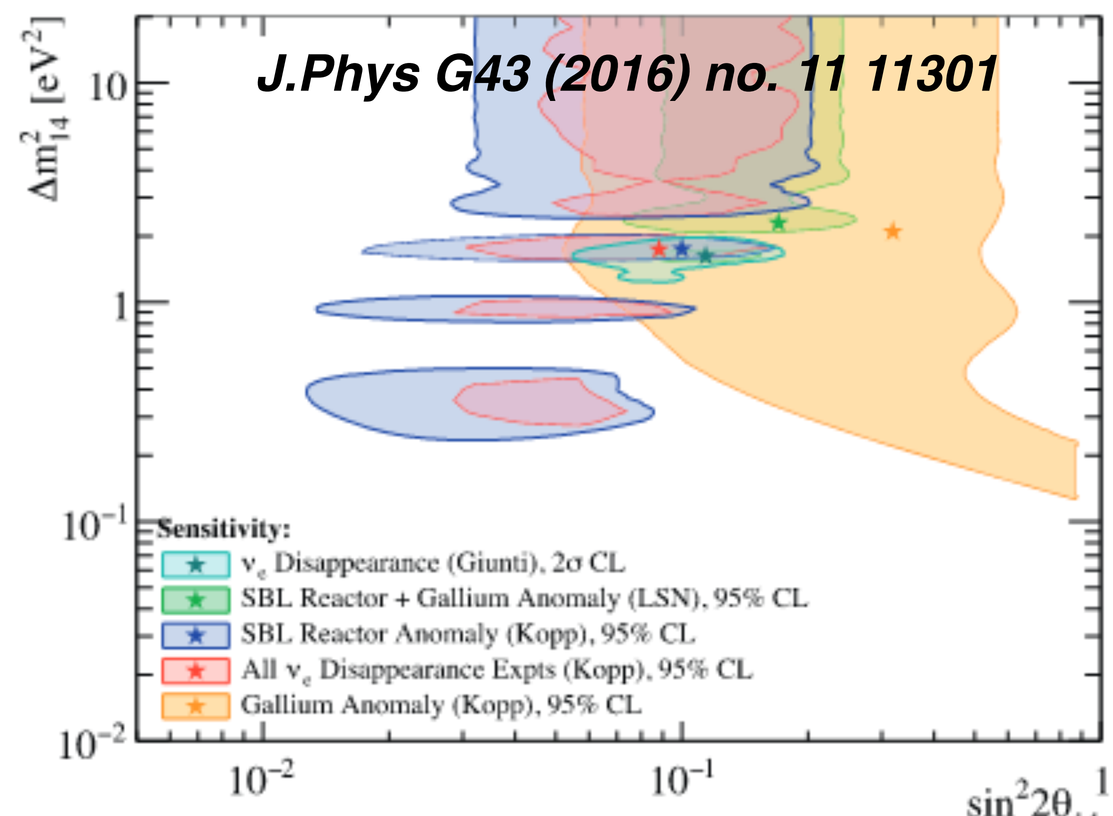


Reactor + Gallium. The dashed purple line is a recent evaluation from Kostensalo … 1906.10980. Reactor best fit is from recent reactor data (NEOS, DANSS, Prospect).

The Reactor Anomaly: $\bar{\nu}_e \rightarrow \bar{\nu}_s$

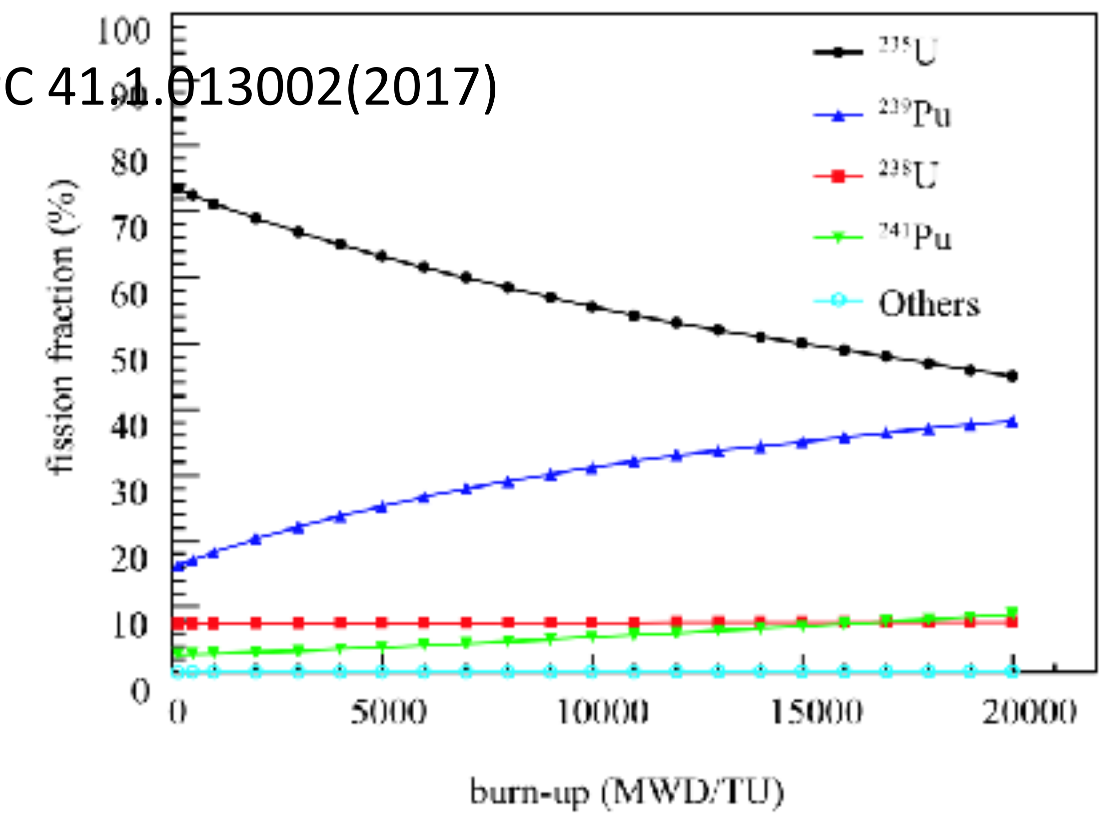


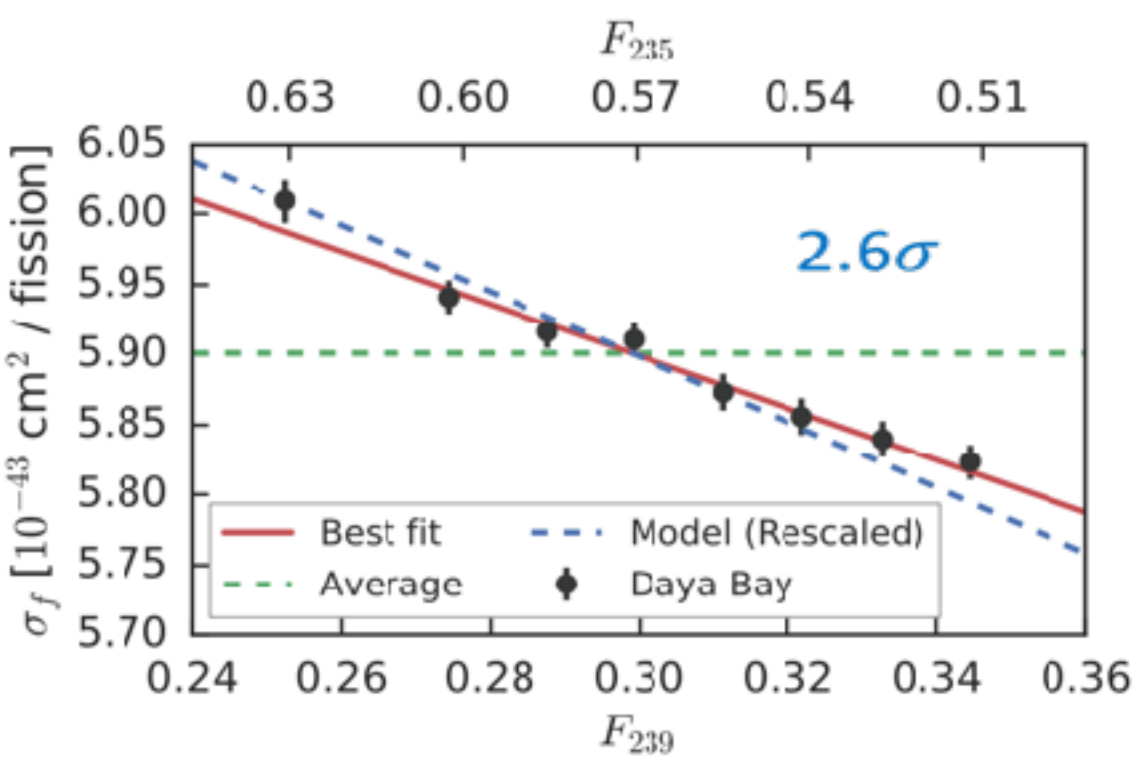
- ***Reactor neutrino flux is based on beta decay data from fission products.***
- ***reevaluations suggests that the neutrino rate has a deficit with respect to the accepted calculations.***
- ***Several reevaluations over decade: Huber-Mueller, ab-initio summation, inclusion of first-forbidden transitions.***
- ***See: 2005.01756 (Berryman, Huber)***
- ***It is quite likely that U235 flux is misestimated.***
- ***RAA =>*** $\sin^2 2\theta = 0.165,\ \Delta m^2 = 2.39 eV^2$



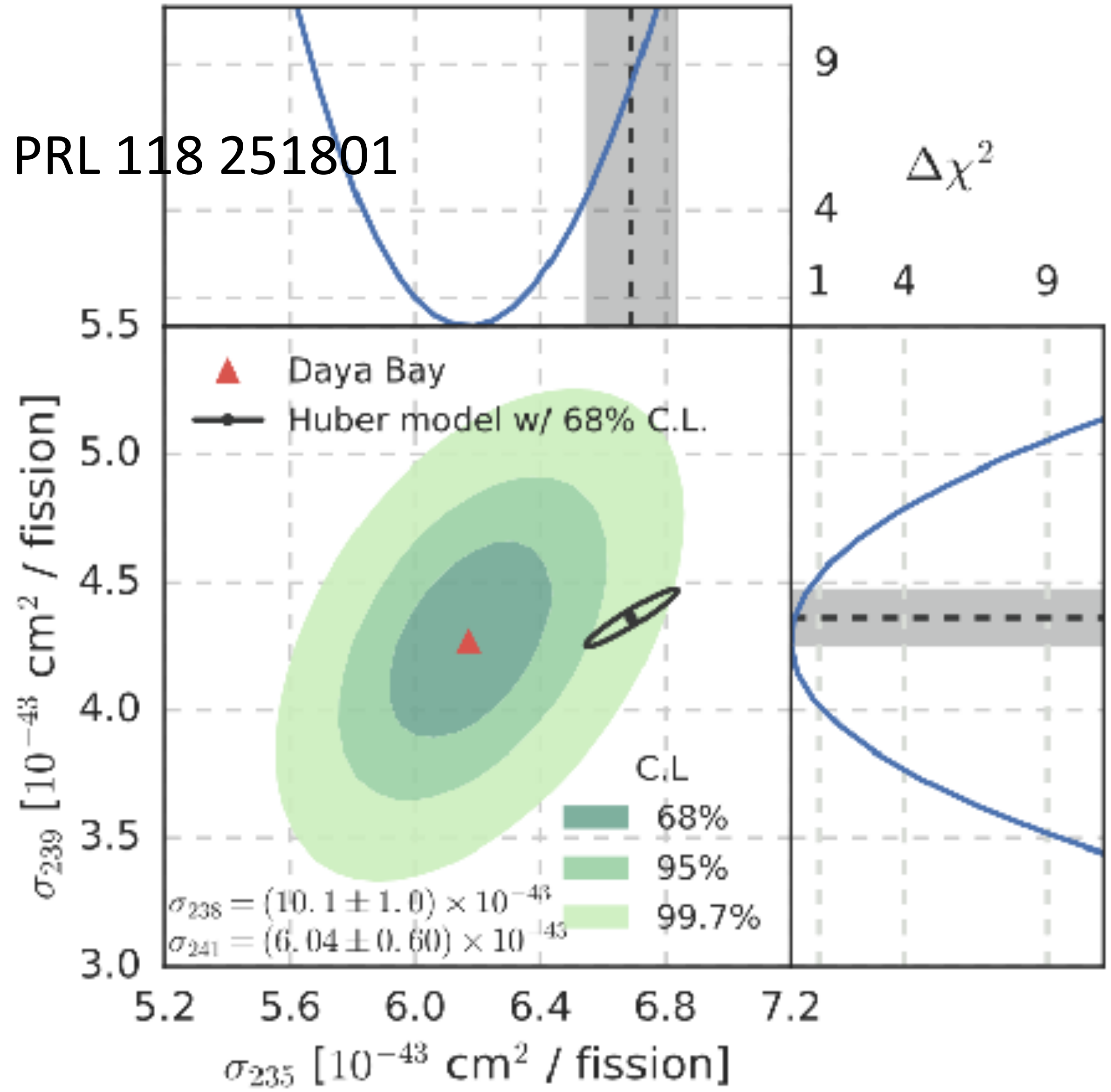
Dayabay Reactor Fuel Evolution Measurement

CPC 41 1 013002(2017)





PRL 118 251801



- Sterile neutrino oscillation requires equal deficit for ^{235}U and ^{239}Pu
- Daya Bay data prefer ^{235}U to be mainly responsible for the reactor anomaly

$$\text{IBD Yield:} \quad \text{Events}_x = \sigma_x \times \text{Total no. of fissions} \times \frac{N_{\text{Targets}}}{4\pi R^2}$$

New work on reactor spectra

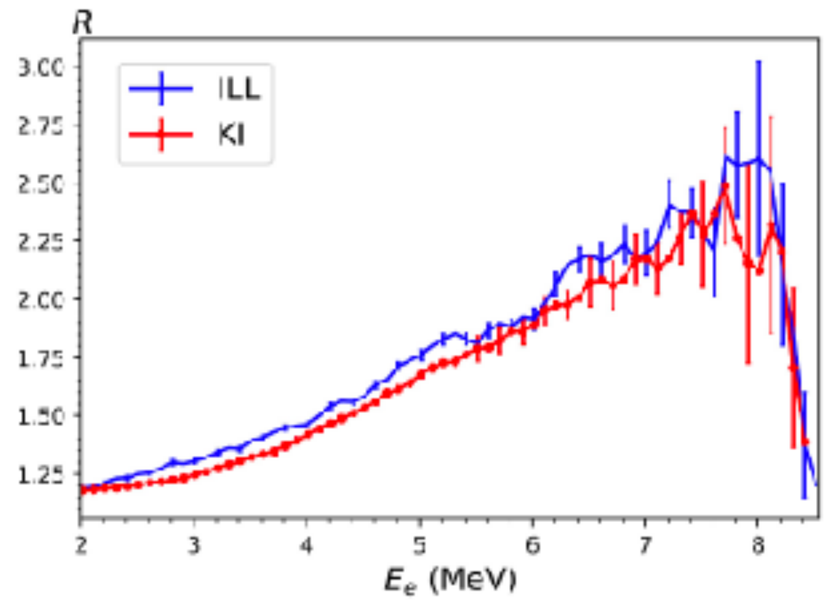


FIG. 1. Ratios $R = {}^eS_5/{}^eS_9$ between cumulative β spectra from ^{235}U and ^{239}Pu from ILL data [11] (blue) and KI data [10] (red). Total electron energies are given. Only statistical errors are shown.

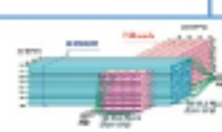
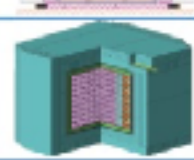
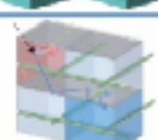
- *V. Kopeikin, et al. 2103.01684*

- ***The antineutrino spectra of 235U, 239Pu and 241Pu were obtained by converting the cumulative beta spectra measured with the BILL spectrometer at the high flux reactor in Institute Laue-Langevin (ILL) in the 1980's. K. Schreckenbach, et al. PLB Vol. 99 (1981) 251. …***
- ***There is new work: V. Kopeikin, et al. 2103.01684. They find that the ILL data has an excess for the U235 yield.***
- ***If this result stands then the RAA will be diminished.***

Short baseline reactor experiments

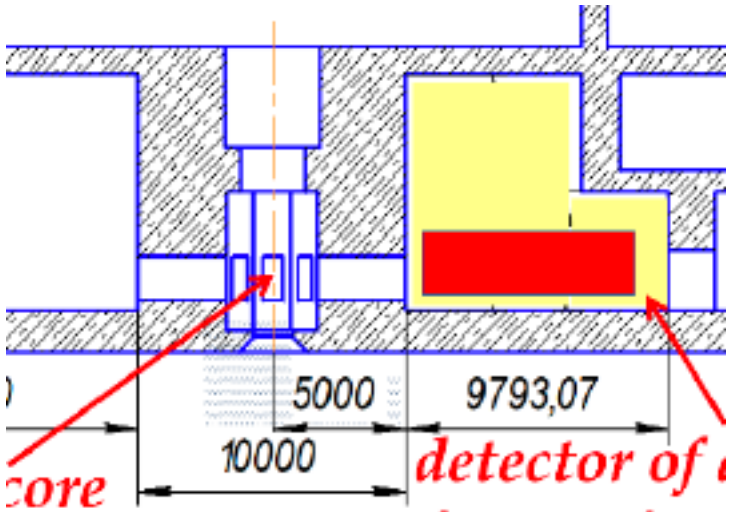
Experimental considerations are
Commercial versus research reactor: size of the core. (~4 m vs ~50cm)
Segmentation and overburden for the detector: background suppression

Mauro Mezzetto, neutrino 2016

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

DANSS, NEOS, Prospect, Stereo, neutrino-4 have results. Neutrino-4 has produced an oscillatory pattern result using L/E bins (in conflict)

Neutrino 4 2005.05301



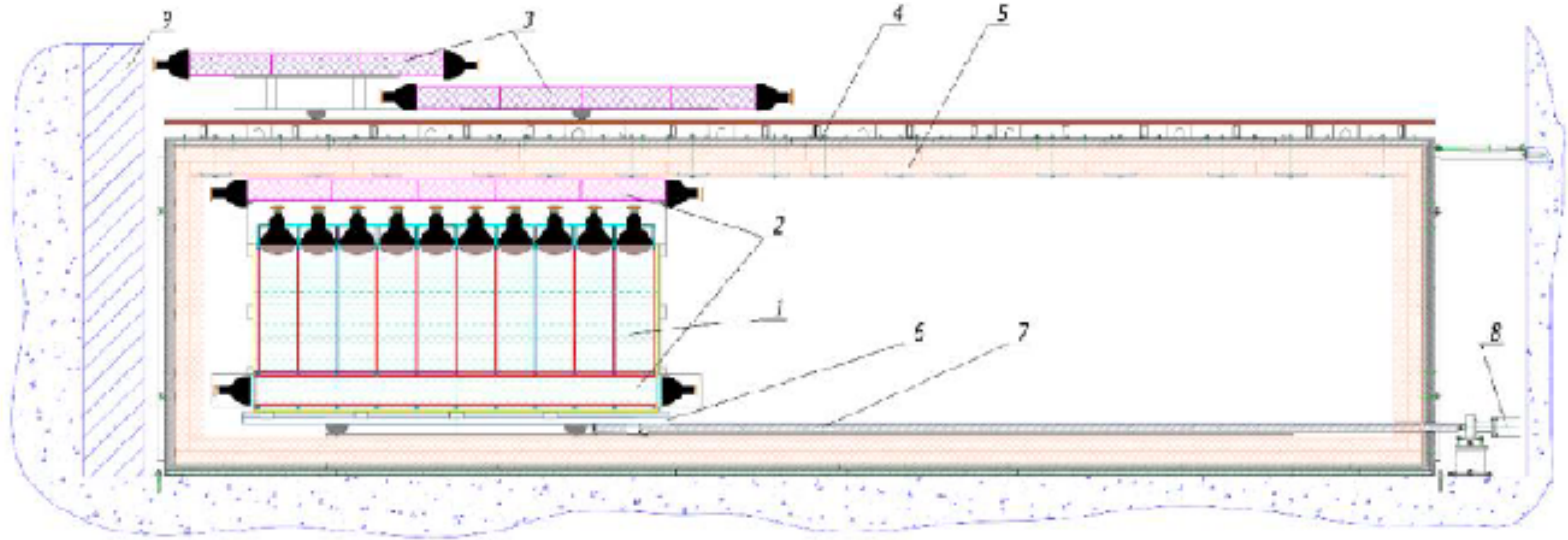
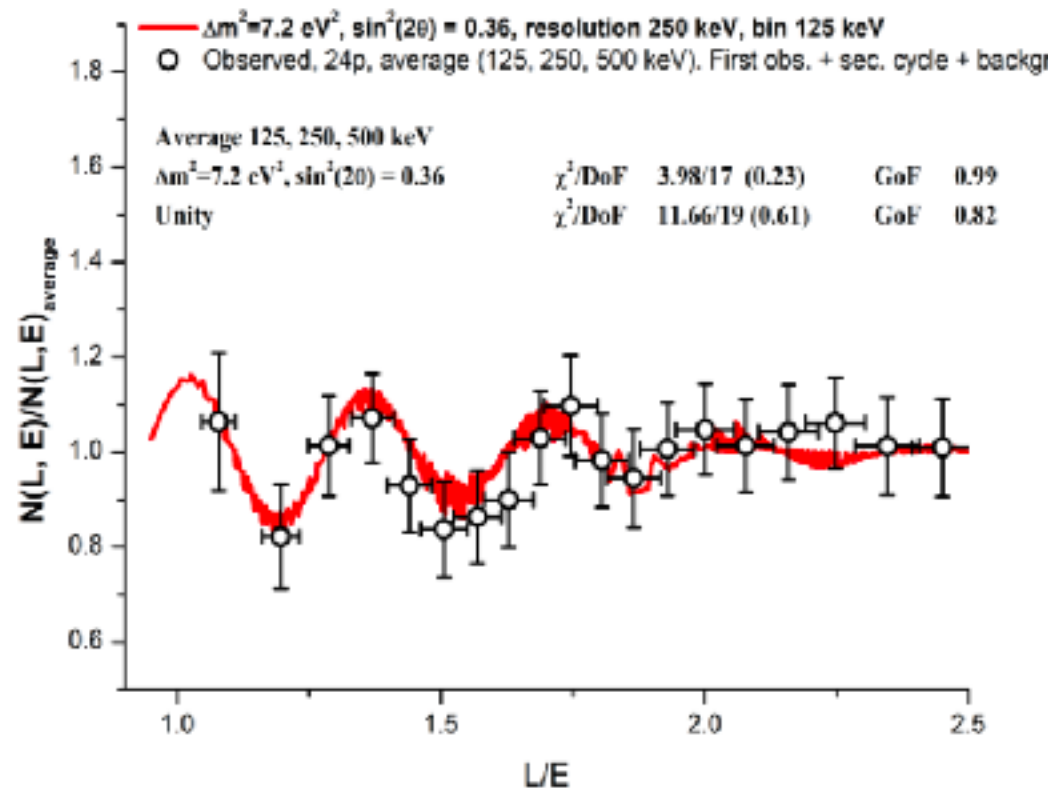


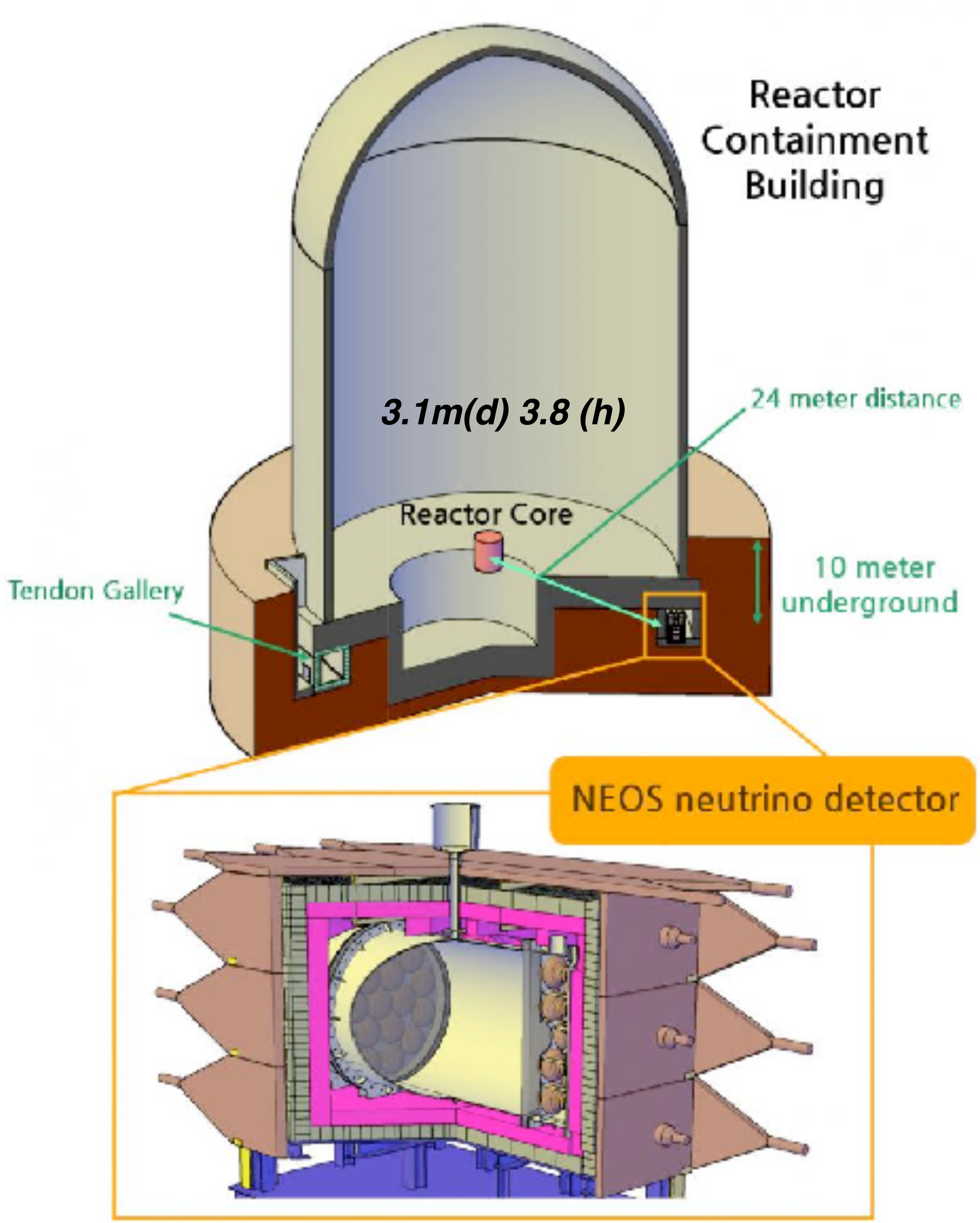
FIG. 18. General scheme of an experimental setup. 1 – detector of reactor antineutrino, 2 – internal active shielding, 3 – external active shielding (umbrella), 4 – steel and lead passive shielding, 5 – borated polyethylene passive shielding, 6 – moveable platform, 7 – feed screw, 8 – step motor, 9 – shielding against fast neutrons made of iron shot

U235 research reactor. 100 MW
Compact core.
Detector movable from 6-12 m.
On-Off measurement to eliminate backg.
Their analysis method is to use coherent summation over L/E measurements.
This is under discussion in various collaboration to get more details on MC, S/B, etc.
Difficult to be sensitive to high delta-m^2



best fit (2.9sigma): $7.3eV^2, \sin^2 2\theta \approx 0.4$

NEOS experiment (new result)



2.8 GW_{th} LEU fuel Hanbit NPP

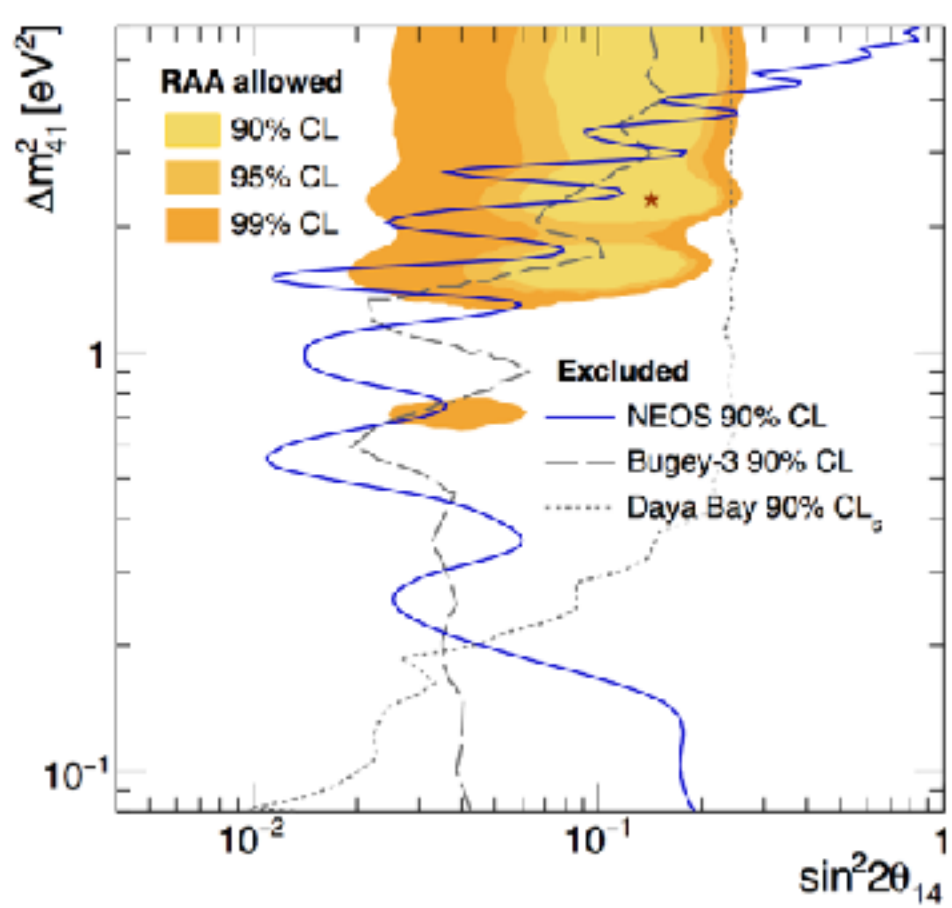
- Yeonggwang, Korea
- Core size: 3.1 m (⏀), 3.8m (H)

Baseline: 23.7 ± 0.3 m

Overburden: > 20 m.w.e.

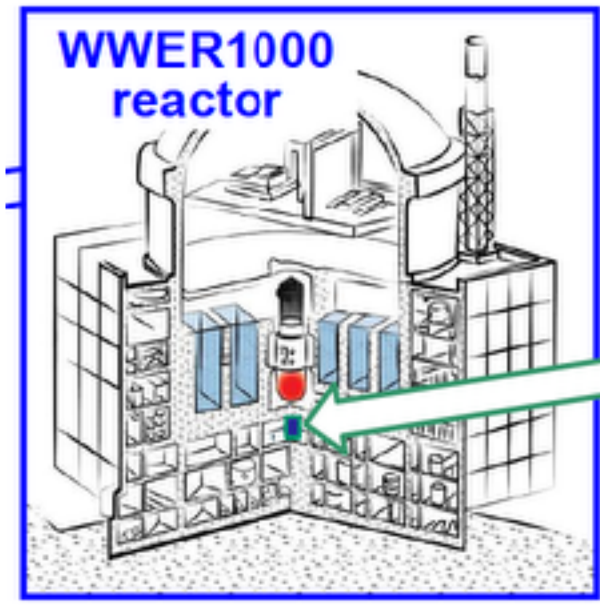
Monolithic Gd-LS

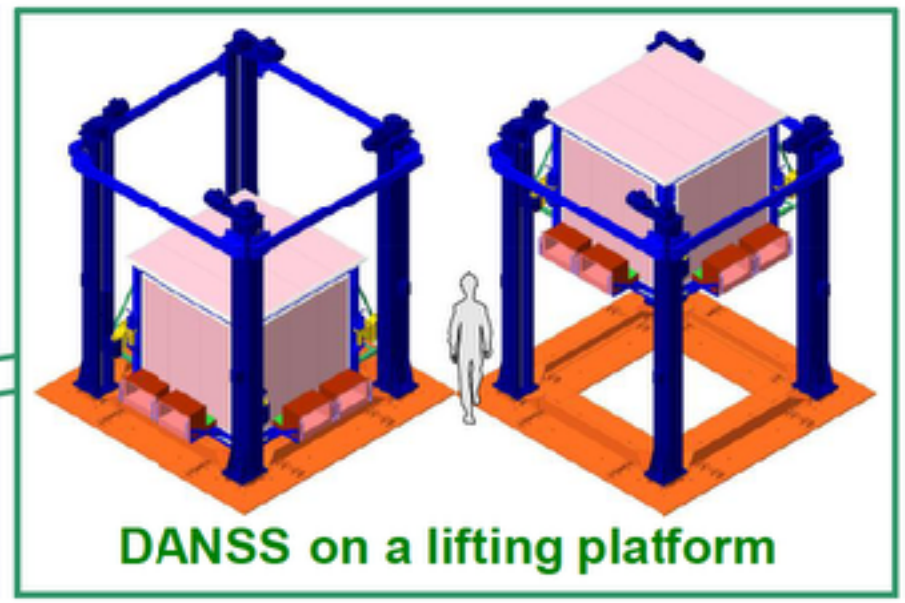
PRL 118, 121802 (2017)

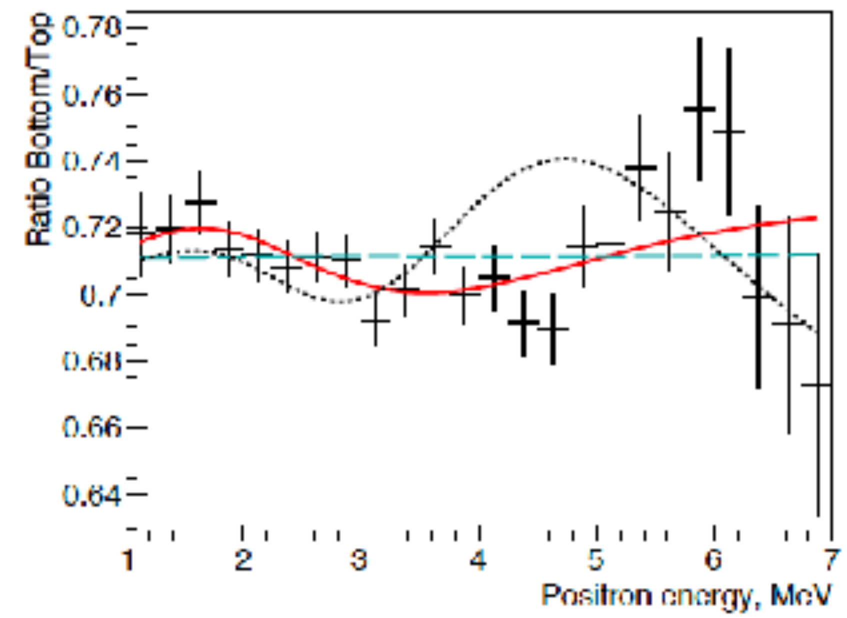


Consistent with Bugey-3's result

DANSS experiment







3.1 GW commercial reactor
50 m.w.e overburden
movable L= 10.7 to 12.7 m
~5k evts/day. PLB 787(2018)56

Analysis - compares spectra at two positions (up/down)

Closer analysis reveals a best fit at
$1.4eV^2;\ \sin^2 2\theta_{14} = 0.05$

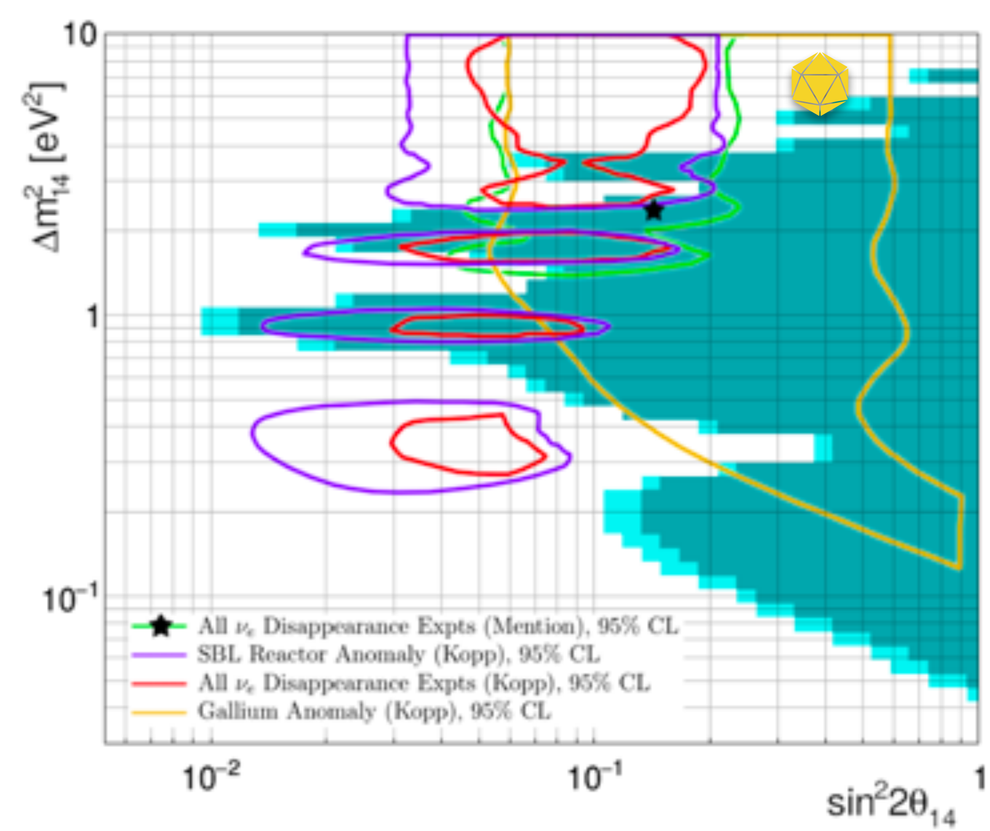
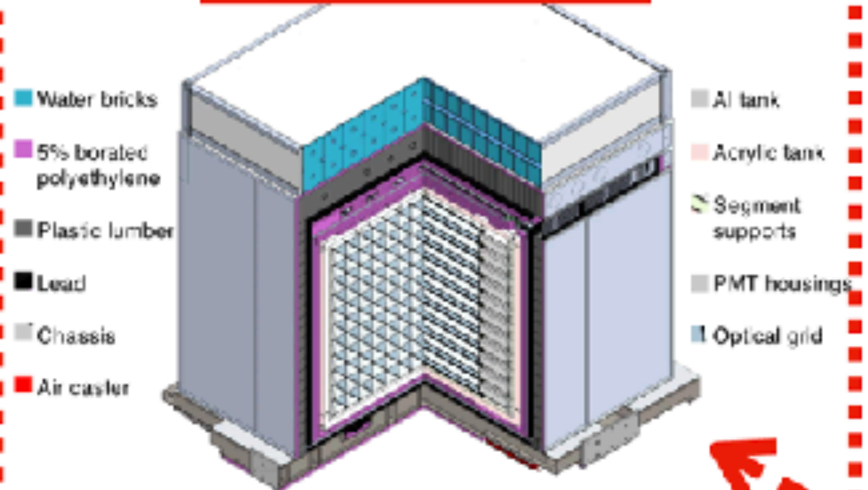


Figure 13: 90% (cyan) and 95% (dark cyan) CL exclusion area in

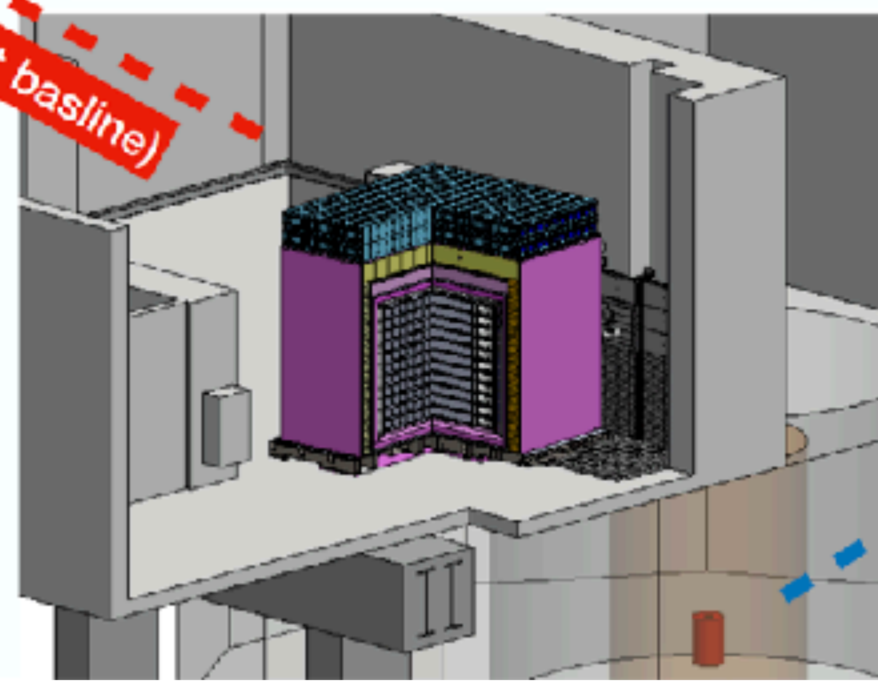
PROSPECT (Precision Oscillation and Spectrum) results.

Segmented Detector



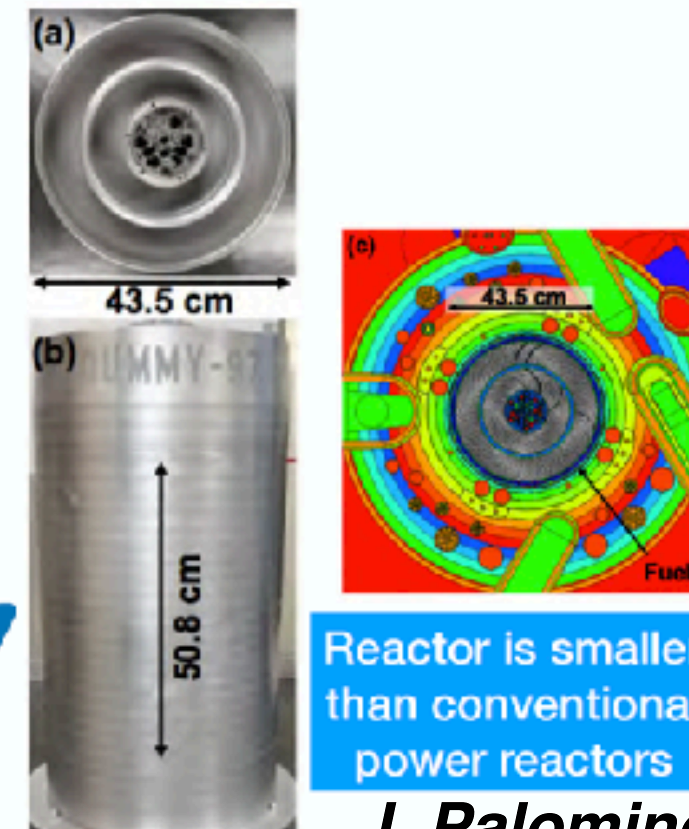
- ~3,000 L 6Li-loaded fiducial volume.
- 11 x 14 array of optically separated segments.
- Double ended PMT readout, with light concentrators.
- Good light collection and energy response ~4.5-5%/√E energy resolution.
- Full X,Y,Z event reconstruction.

HIGH FLUX ISOTOPE REACTOR AT OAK RIDGE NATIONAL LABORATORY



Reactor Core highly-enriched (HEU):
>99% of ν_e flux from ^{235}U fission:

- Power: 85 MW
- Core shape: cylindrical
- Size: h=0.5m d=0.4m
- Duty-cycle: 24 days cycle

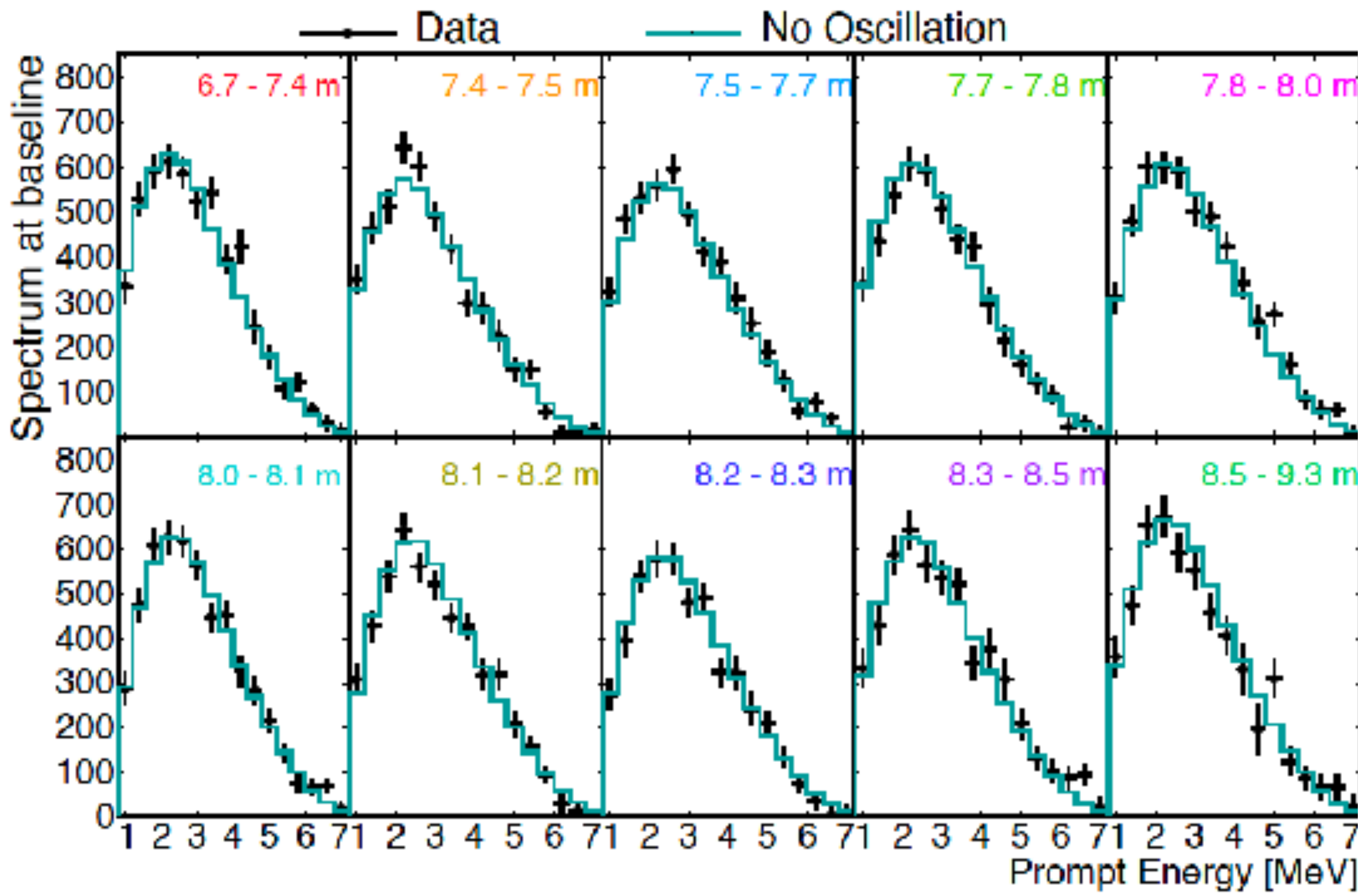


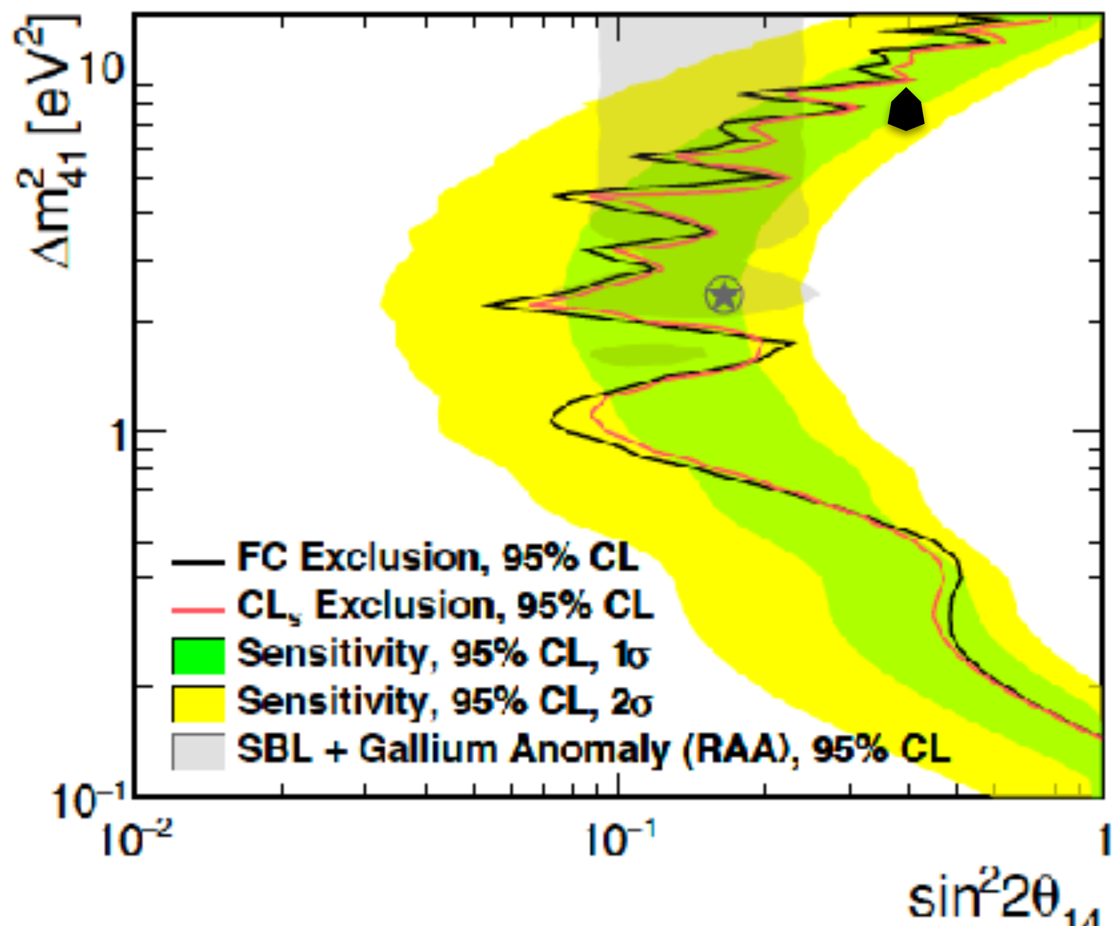
Reactor is smaller than conventional power reactors

J. Palomino

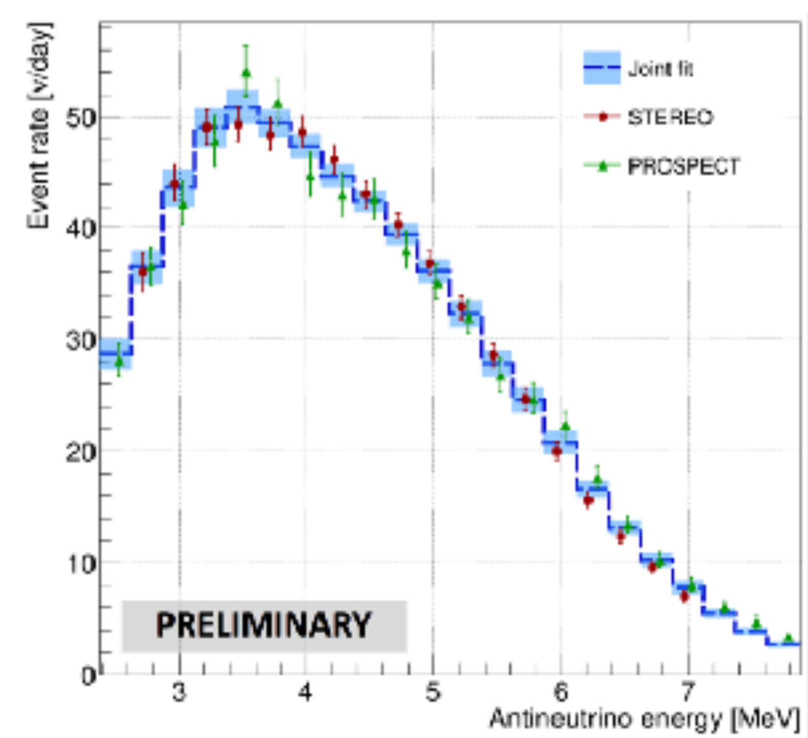
- ***The detector is on surface.***
- ***Segmentation, excellent pulse shape discrimination allows sufficient backg reduction***

PROSPECT results 2006.11210





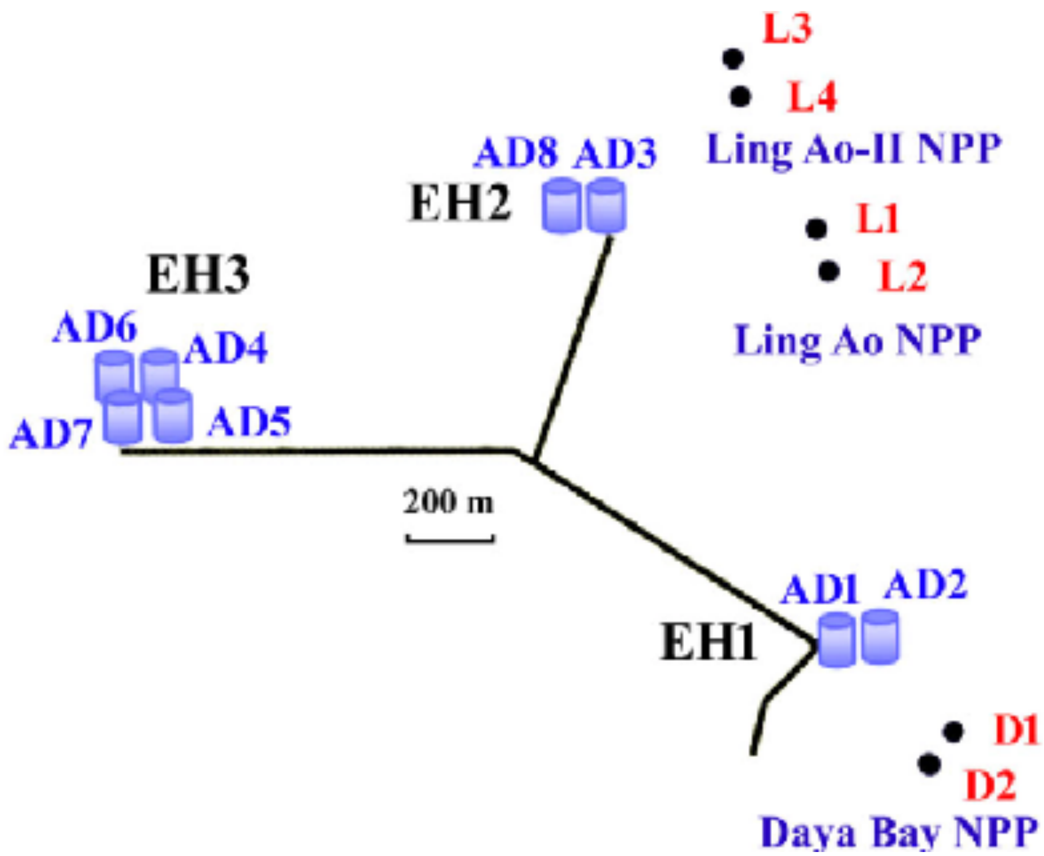
- PROSPECT has spectra from many distances with broad sensitivity and good systematics.
- Also produced fit to spectra with Stereo for a pure U235 neutrino spectra.
- There is no overwhelming evidence for RAA in any of the current round.
- PROSPECT will have an upgrade to fix PMT instabilities for much more data.

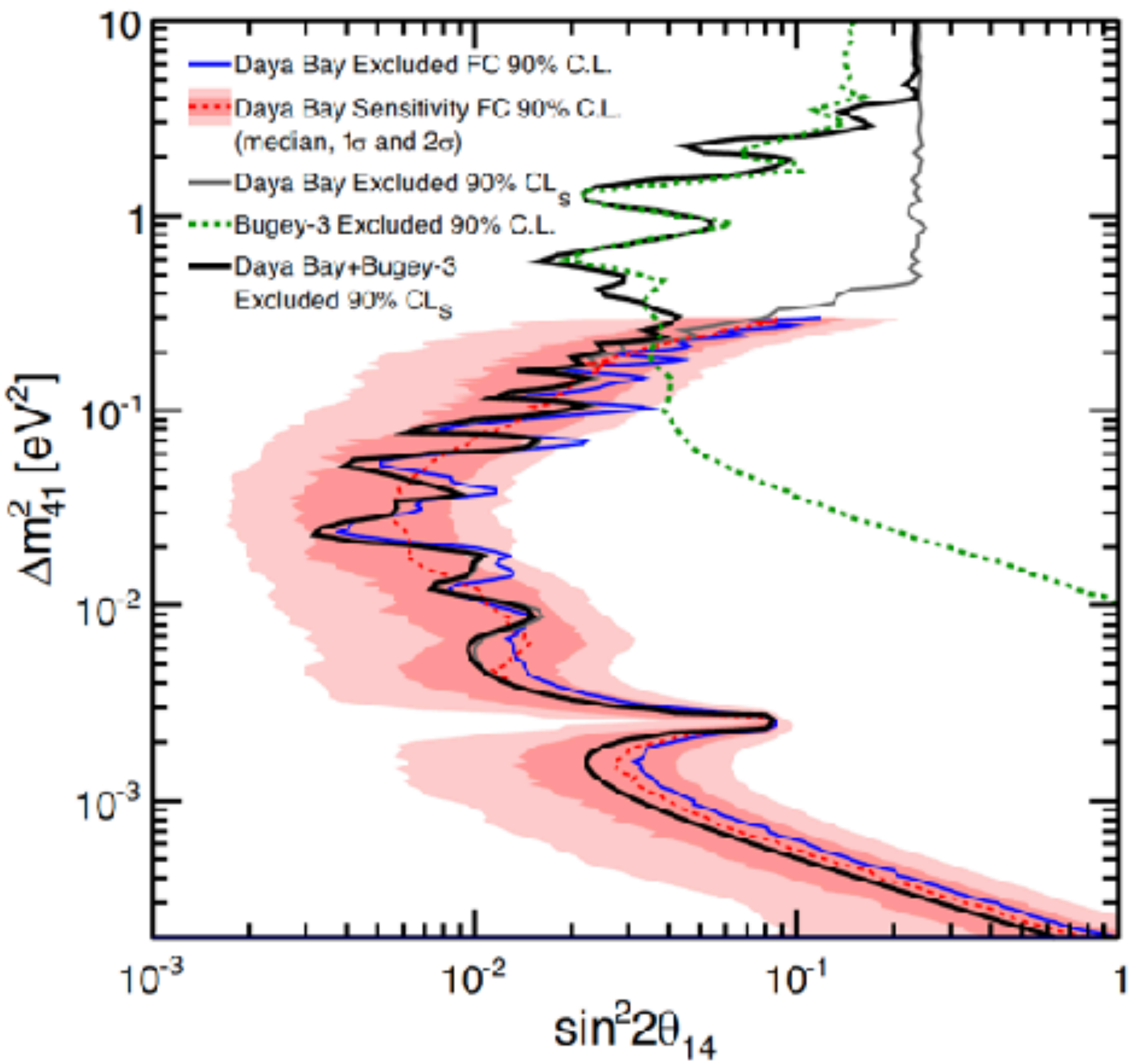


The Daya Bay Experiment

Daya Bay reactor complex: 2.9 x 6 GW_{th}, PWR

PRL 117, 151802 (2016)
PRL 125, 071801 (2020)

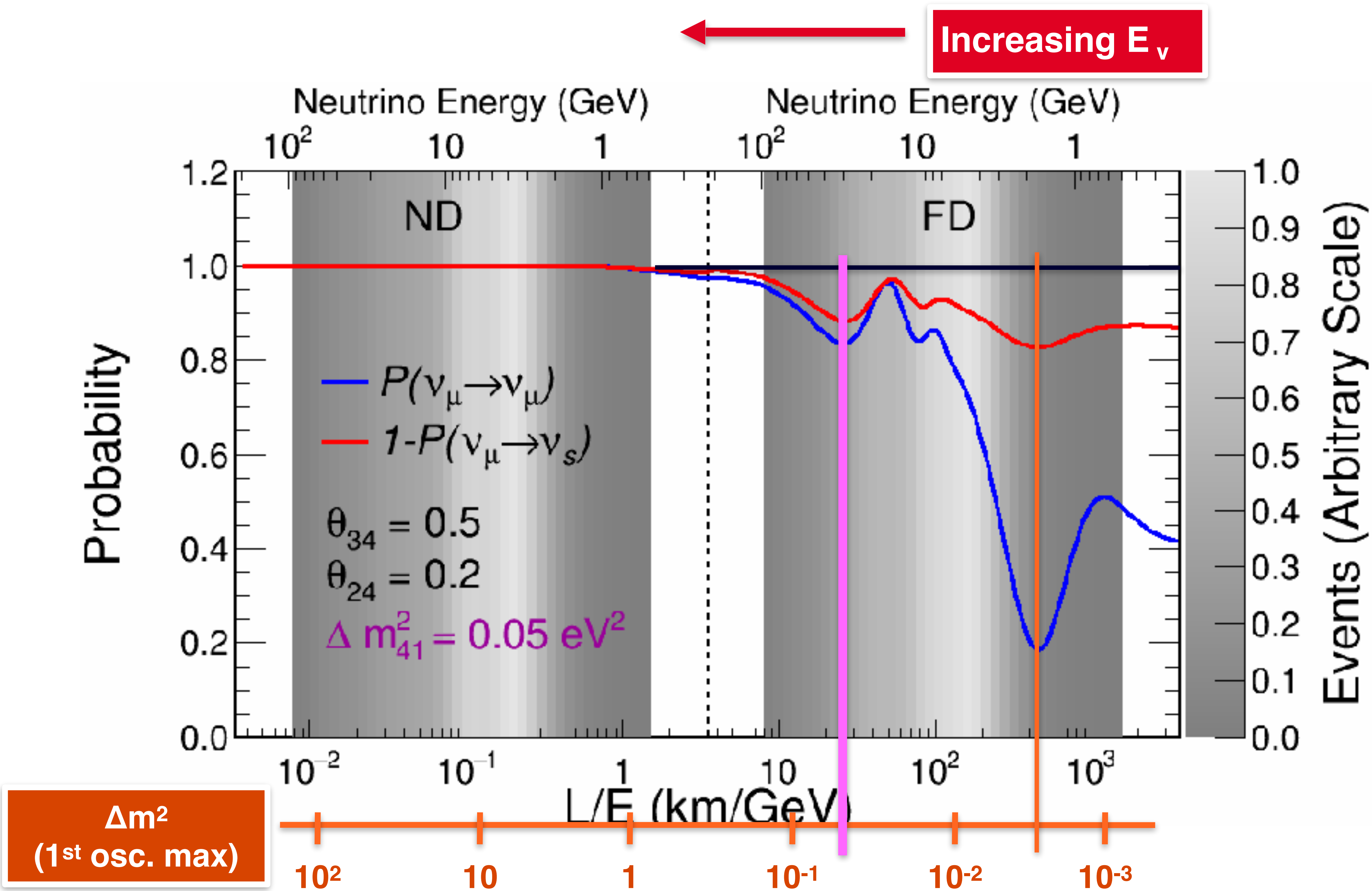




Site	Mean distance to reactor cores (m) Daya Bay	Ling Ao	Ling Ao–II
EH1	365	860	1310
EH2	1348	481	529
EH3	1909	1537	1542

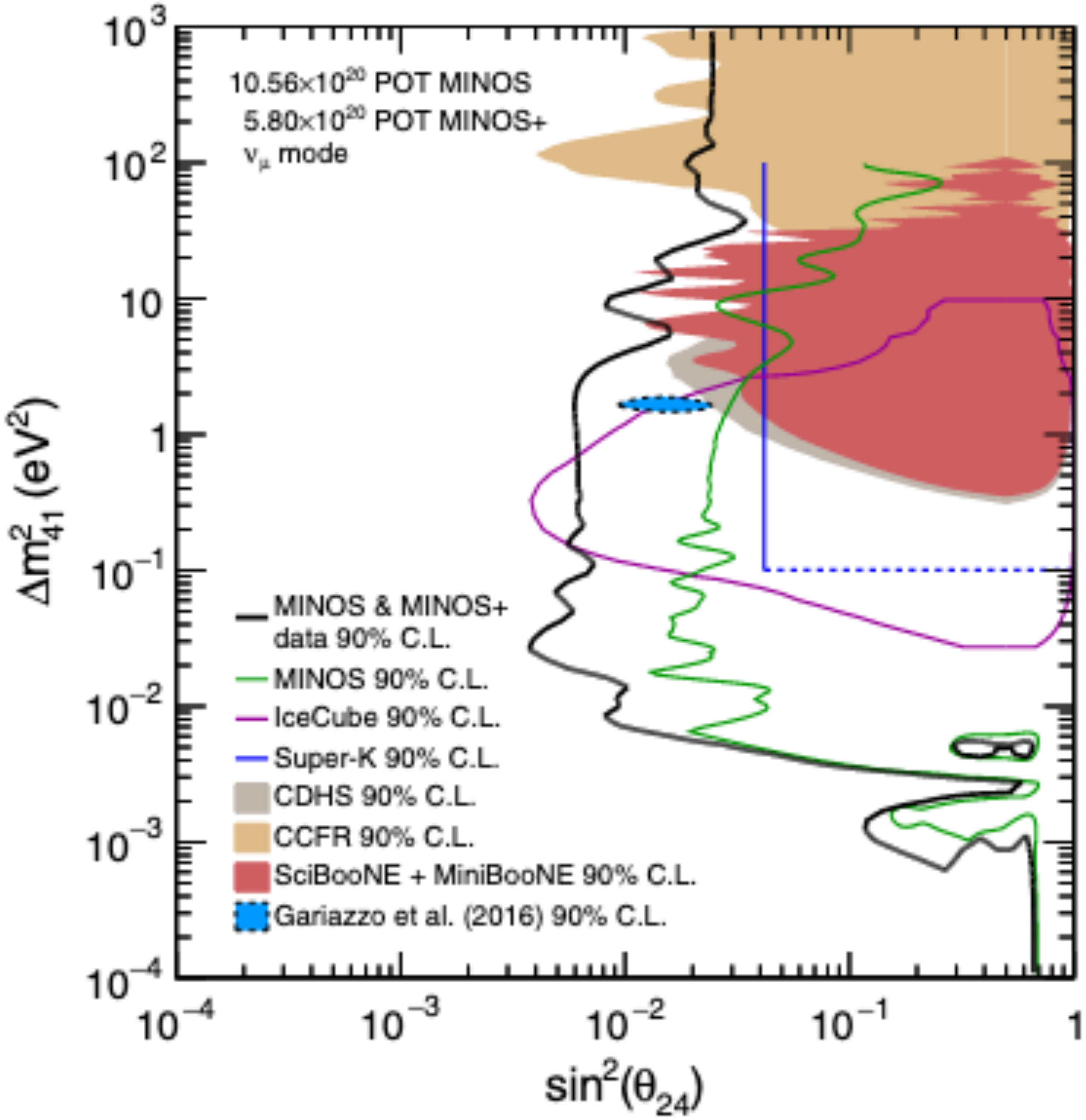
Wide L/E range allows sensitivity over 3 decades. Combined with Bugey-3 to get sensitivity from 0.1-few eV^2.

3(active)+1(sterile) oscillation pattern in MINOS detectors

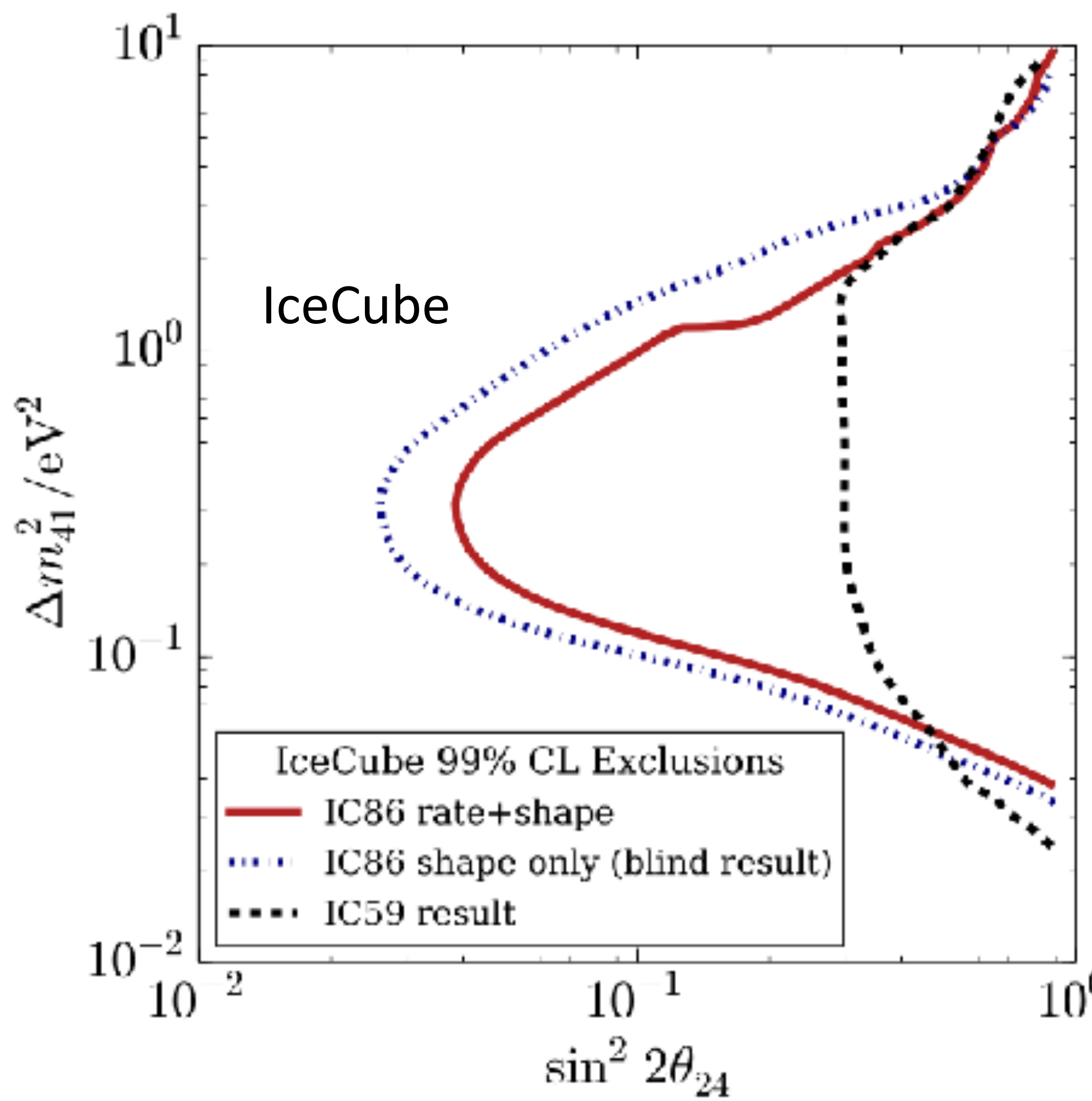


ν_s Search in $\nu_\mu \rightarrow \nu_\mu$ Channel

PRL 122, 091803 (2019) MINOS



PRL 117, 071801 (2016)

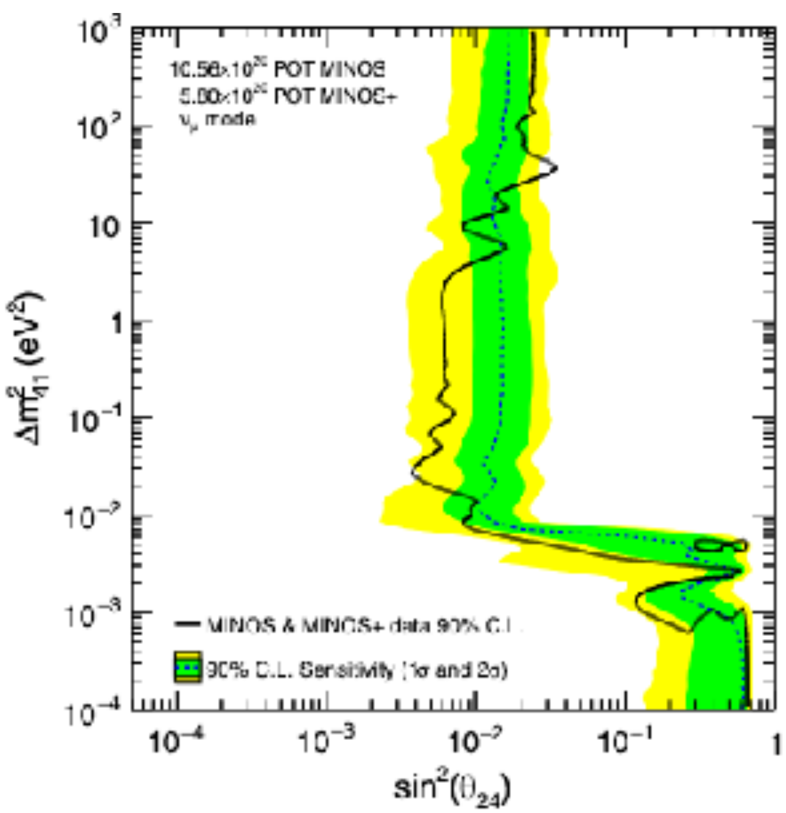


MINOS ran with 3 GeV beam for many years. MINOS+ ran with beam peaked at 7 GeV. Fit to both ND and FD data was performed. The icecube limit comes from the realization of the earth's matter effect in this energy region.

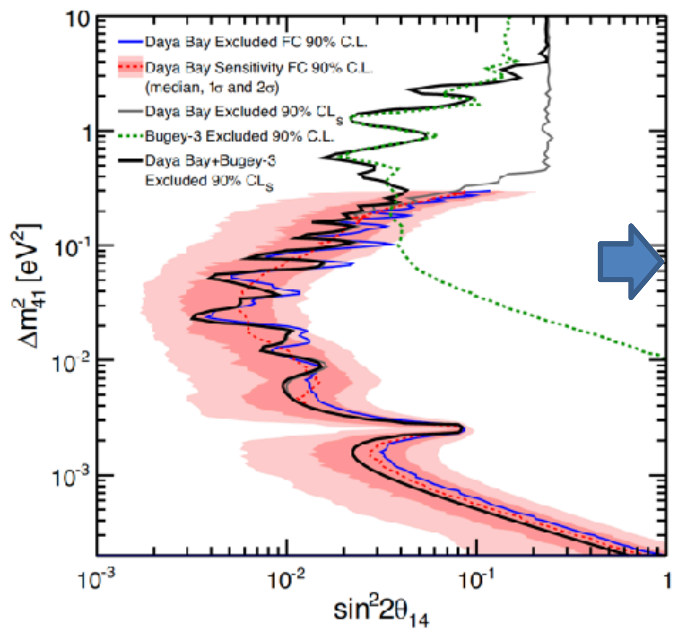
Joint Analysis of Daya Bay/Bugey-3/MINOS

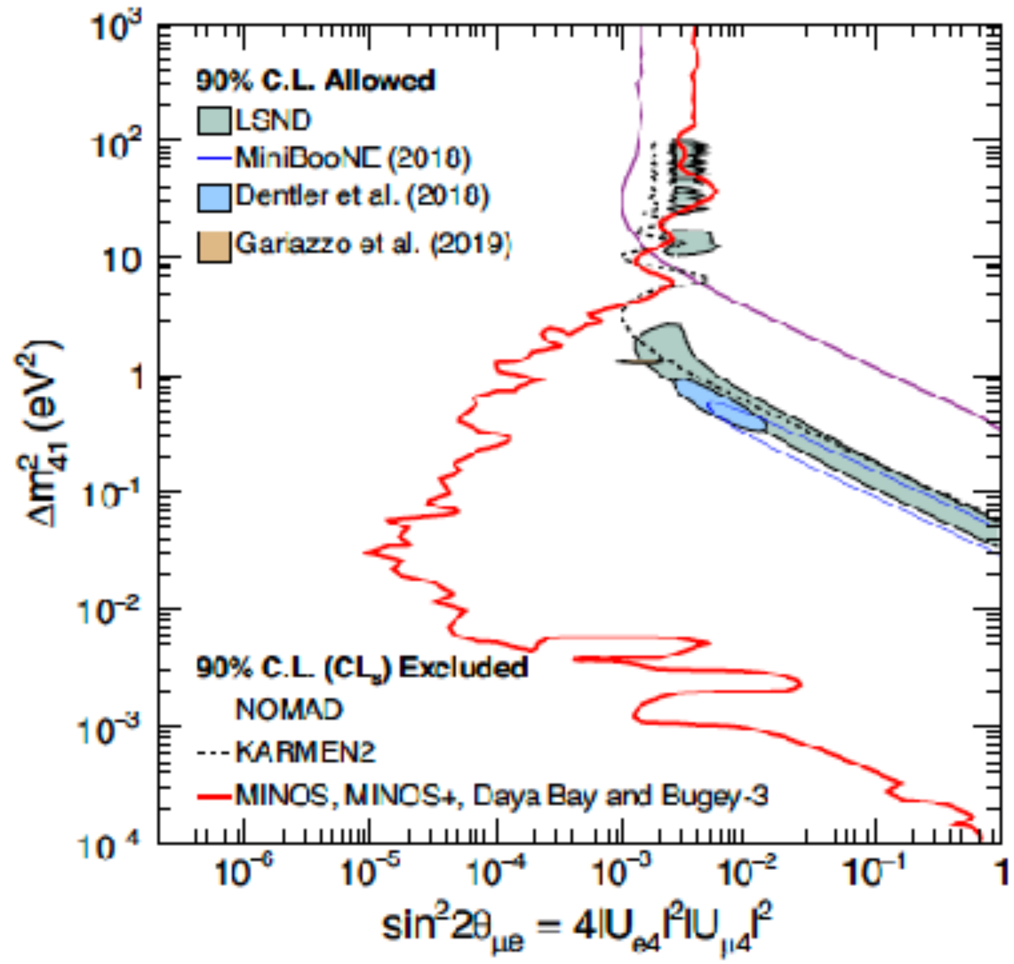
Recall $$\sin^2 2\theta_{\mu e} = \frac{1}{4}\sin^2 2\theta_{\mu\mu}\sin^2 2\theta_{ee}$$

MINOS/MINOS+



Daya Bay + Bugey-3

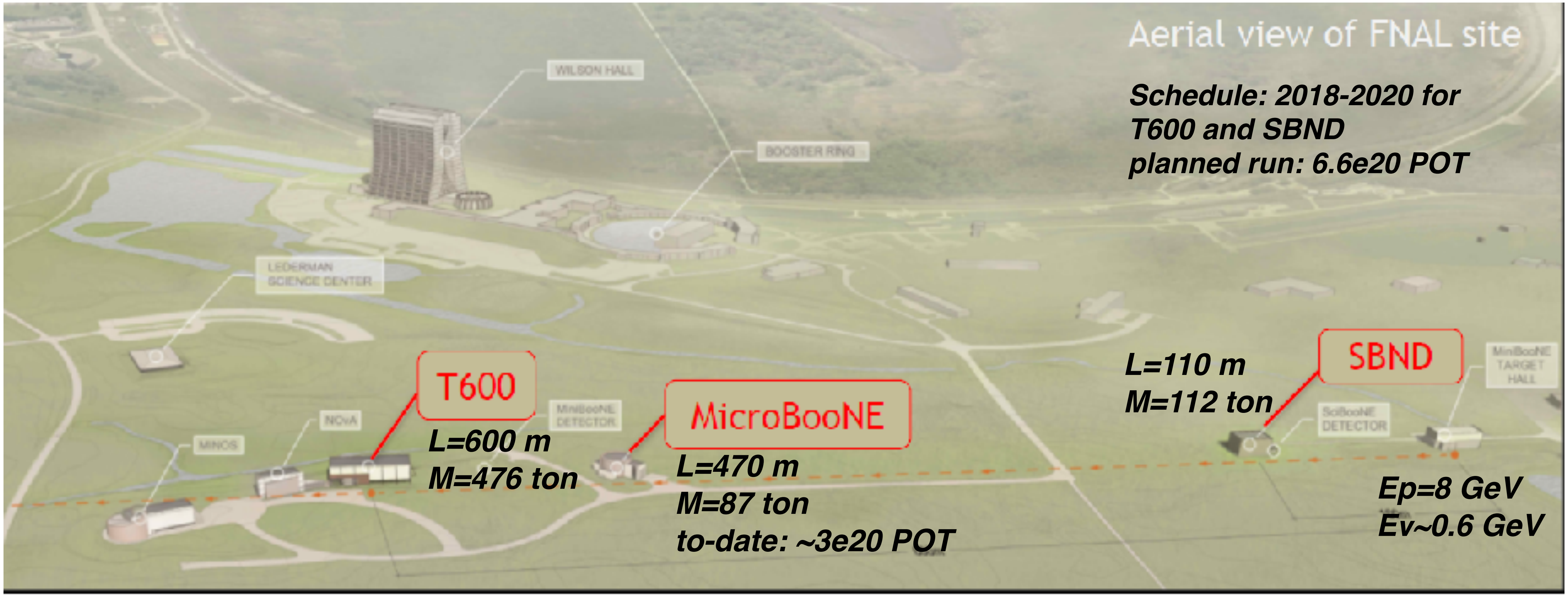


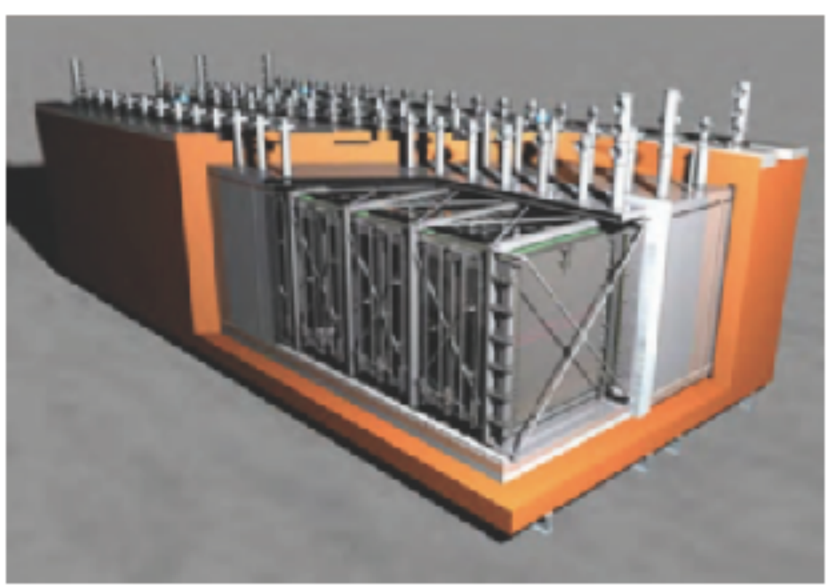


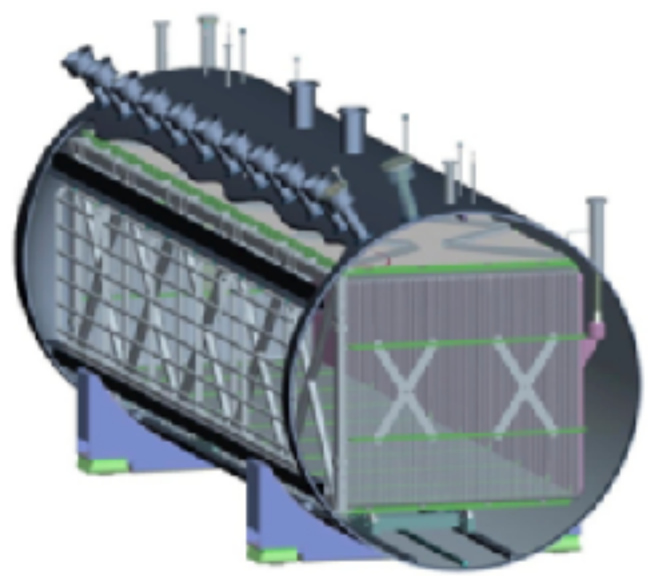
- The combined limit for 3+1 can be very strong around ~0.1-1 eV2.
- The combined results can largely exclude the LSND and MiniBooNE region assuming 3+1 neutrino model
- The paper has 99% contours. The upper lobes (>10 eV^2) escape the constraint.

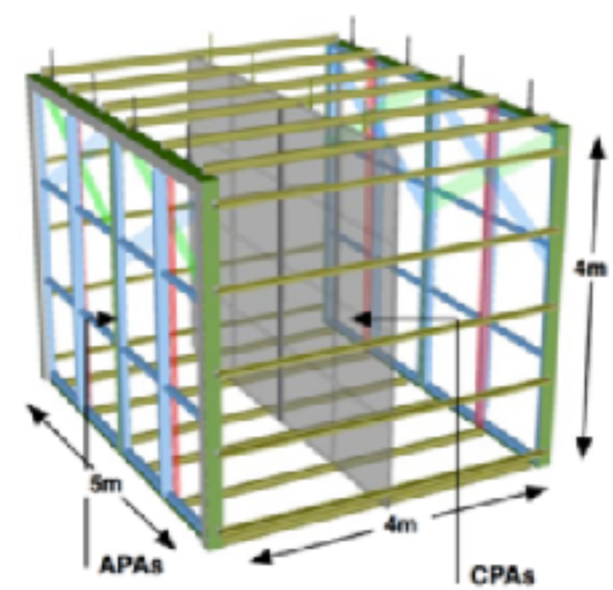
Combined : Phys. Rev. Lett. 125, 071801 (2020)
MINOS : Phys. Rev. Lett. 122, 091803 (2019)
Daya Bay : Phys. Rev. Lett. 117, 151802 (2016)

Fermilab Short Baseline program

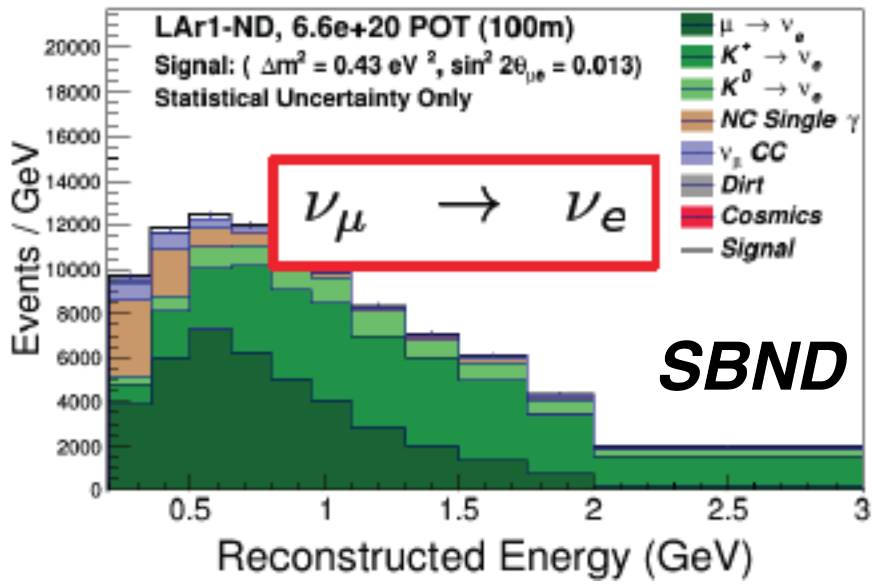


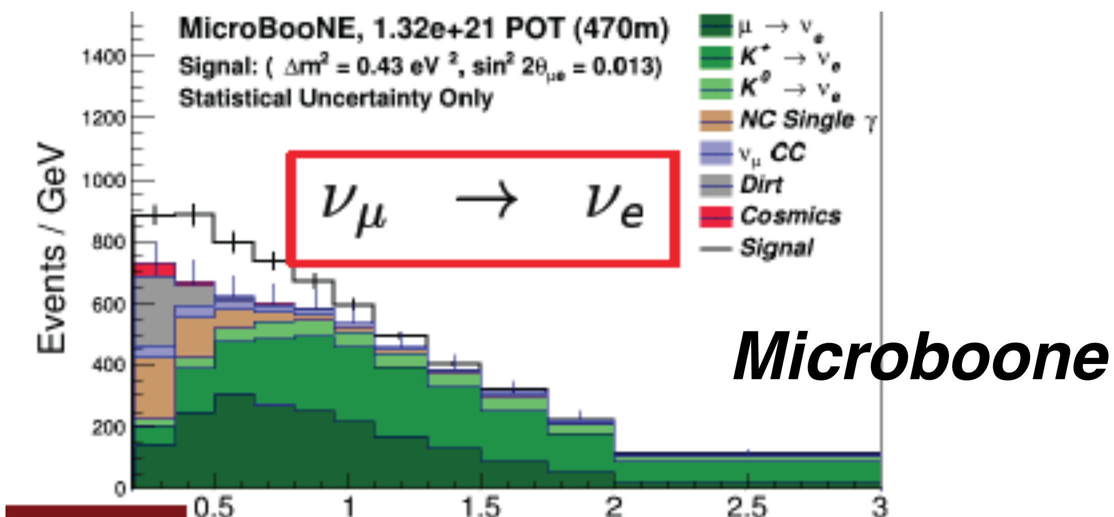


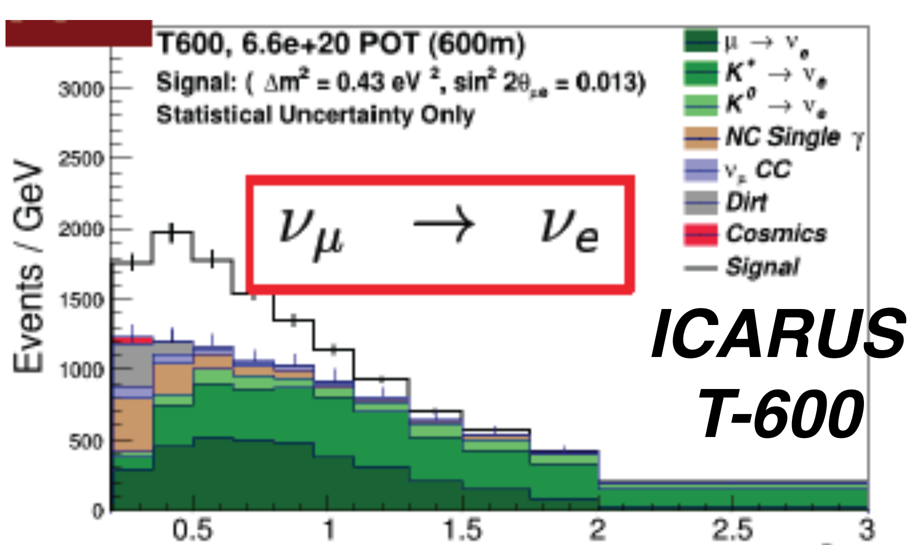




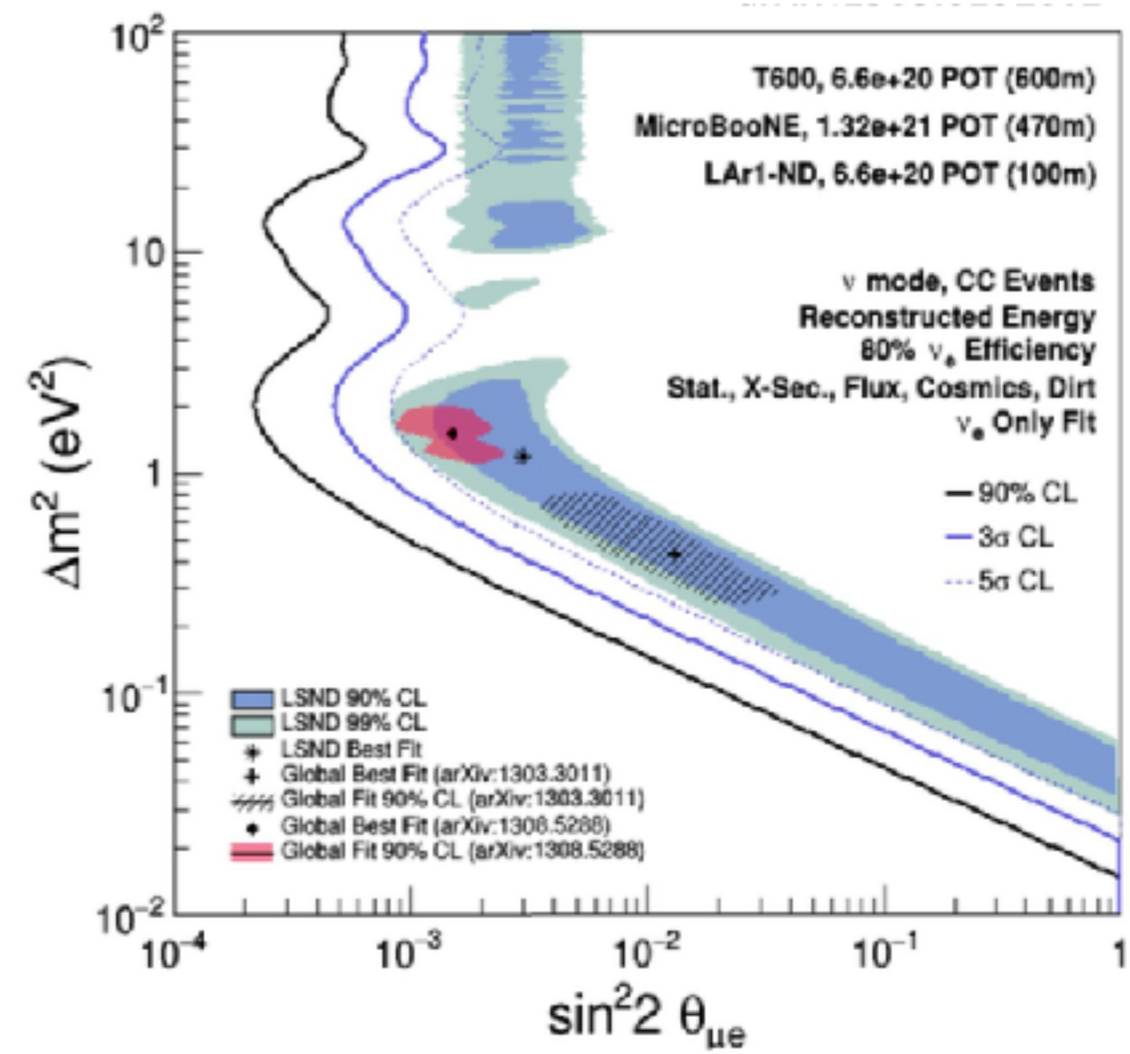
FNAL Short-baseline program.







arXiv: 1503.01520



Background reduction depends on detailed event reconstruction and e/γ separation by gap and dedx.

Performance depends on geometry/electronic noise. (mind the gap).

The 3-detector approach should be an excellent cross check on the backgrounds and systematics

SBN status

- ***MicroBoone: Analysis in progress and will report soon.***

- ***ICARUS: Detector ready, taking data. Work ongoing on calibration, noise reduction, and trigger.***

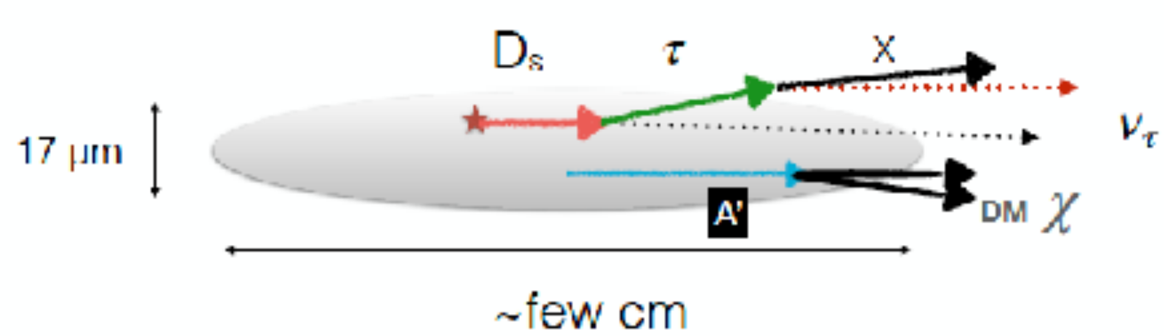
- ***SBND: Detector under construction. Estimated 2022.***

ICARUS status Sep 2019, TPC and PMT systems have been taking data for many months. Cryo system is stable with > 3 ms lifetime. This will soon be covered up by cosmic ray tagger.

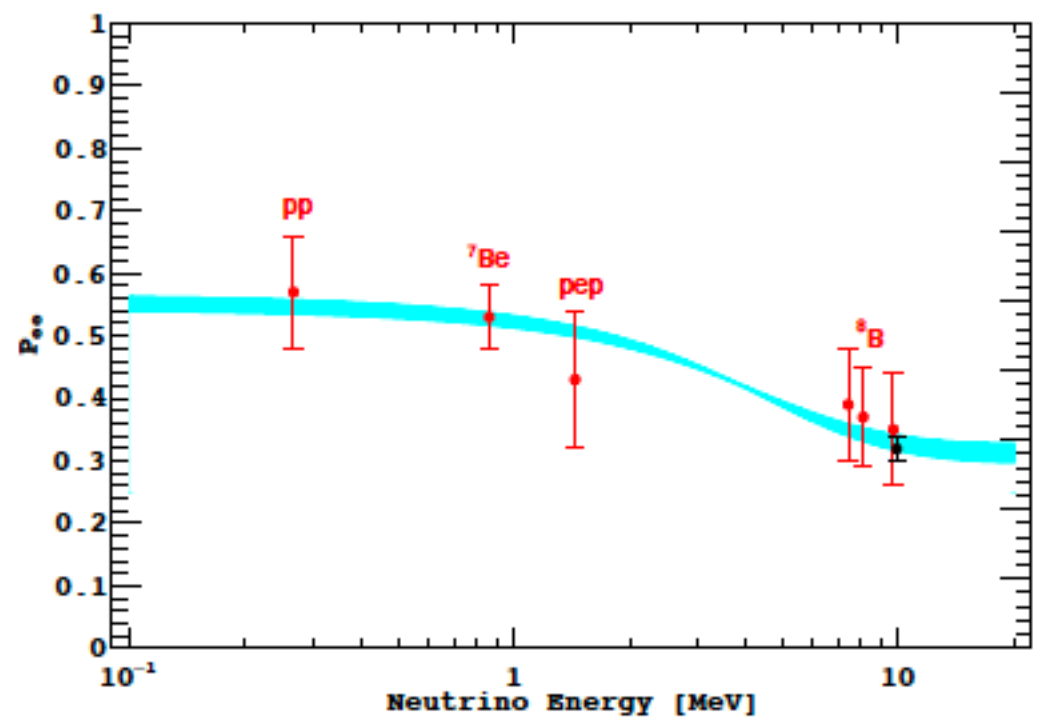
New ideas for beyond 3 neutrinos ?

- ***There is a new evaluation in progress at CERN for a forward physics facility (FPF) to look at the beam from the collision. This would the first tau neutrino beam. If the tau neutrino beam can be characterized well then this would allow access to nutau disappearance. (SBU student: Karan Kumar)***

- ***What about a new solar neutrino experiment ?***



HL-LHC 14 TeV



Conclusions

- ***There is good motivation for sterile neutrino search over a wide mass range. Such a broadband search is very difficult.***
- ***We should pay attention to results from cosmology, astrophysics, beta decay, and neutrino-less double beta decay, and CLFV (e.g., $\mu \rightarrow e$). tritium beta decay (Katrin) might become the best limit in the > 3eV range.***
- ***The disappearance results from MINOS, and Daya Bay and combination is very robust and in conflict with appearance.***
- ***Current search of oscillations around 1 eV is likely to conclude in the near future with many new experimental results.***
- ***Are sterile neutrinos 1) relevant ?(yes), 2)experimentally accessible ? (partly), 3) already observed ? (probably not).***
- ***There are important technical lessons to be learnt from previous experiments regarding backgrounds and systematics.***
- ***"We all need to work harder," Maurice Goldhaber***

Evidence from LSND anti-$\nu_\mu \rightarrow$ anti-ν_e

p-beam: LAMPF in Los Alamos National Lab. 798 MeV at 1 mA
Neutrinos from decay at rest (DAR)

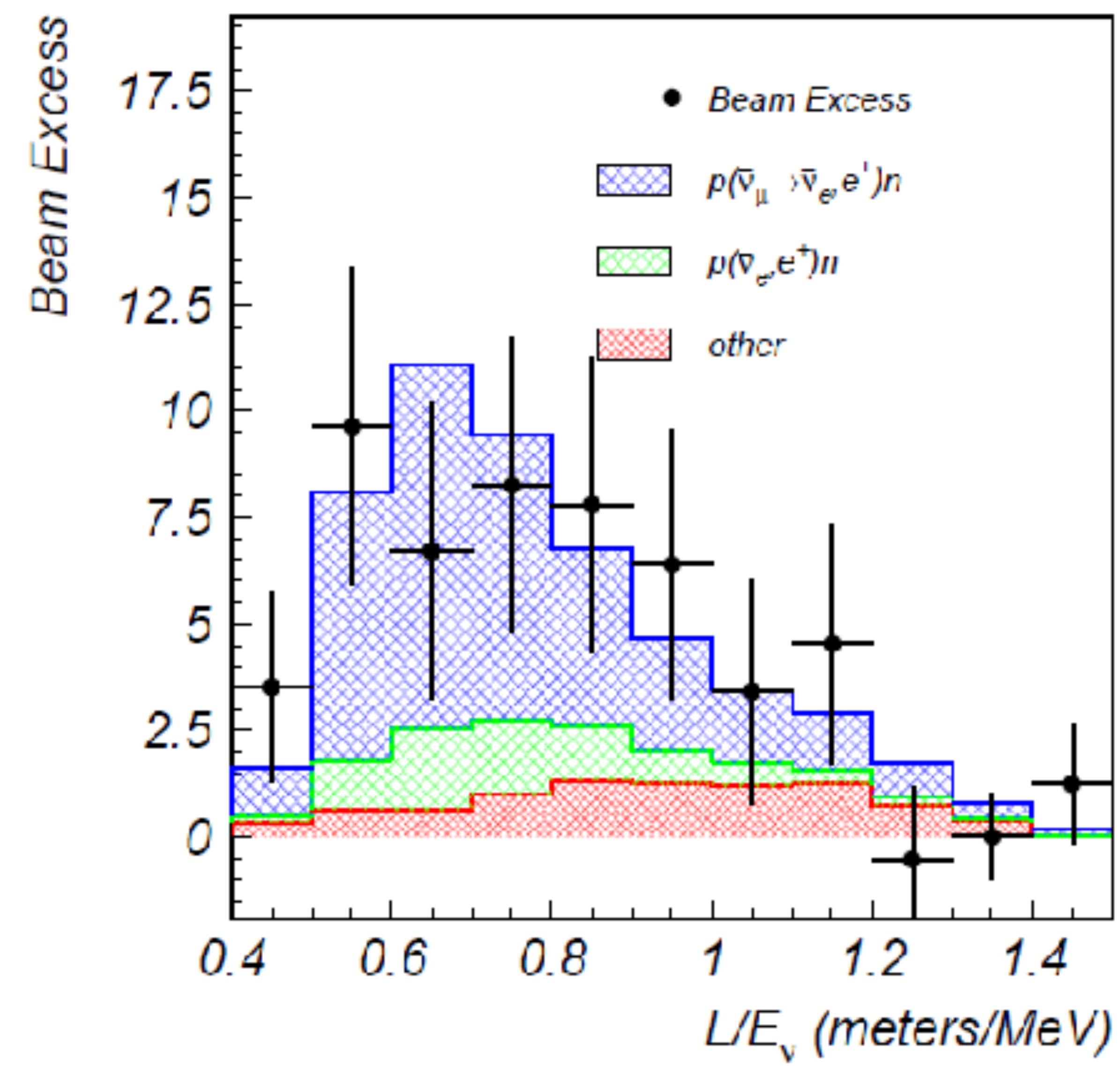
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Oscillation mode: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Detection mode: $\bar{\nu}_e + p \rightarrow e^+ + n$
Baseline: 30 m
Energy range: 20 – 60 MeV
L/E : ~ 1 m / MeV

Signal: inverse beta decay positron with a gamma from n absorption

Event excess: 87.9+-22.4+-6.0 (3.8σ)

Phys. Rev. D64, 112007 (2001)



plot of a subset of data with good n-tag

- backgrounds: beam-off, μ^- DAR, and π^- Decay in flight.
- implies at least 4 mass eigenstates: $\Delta m^2_{sol} << \Delta m^2_{atm} << 1$ eV^2

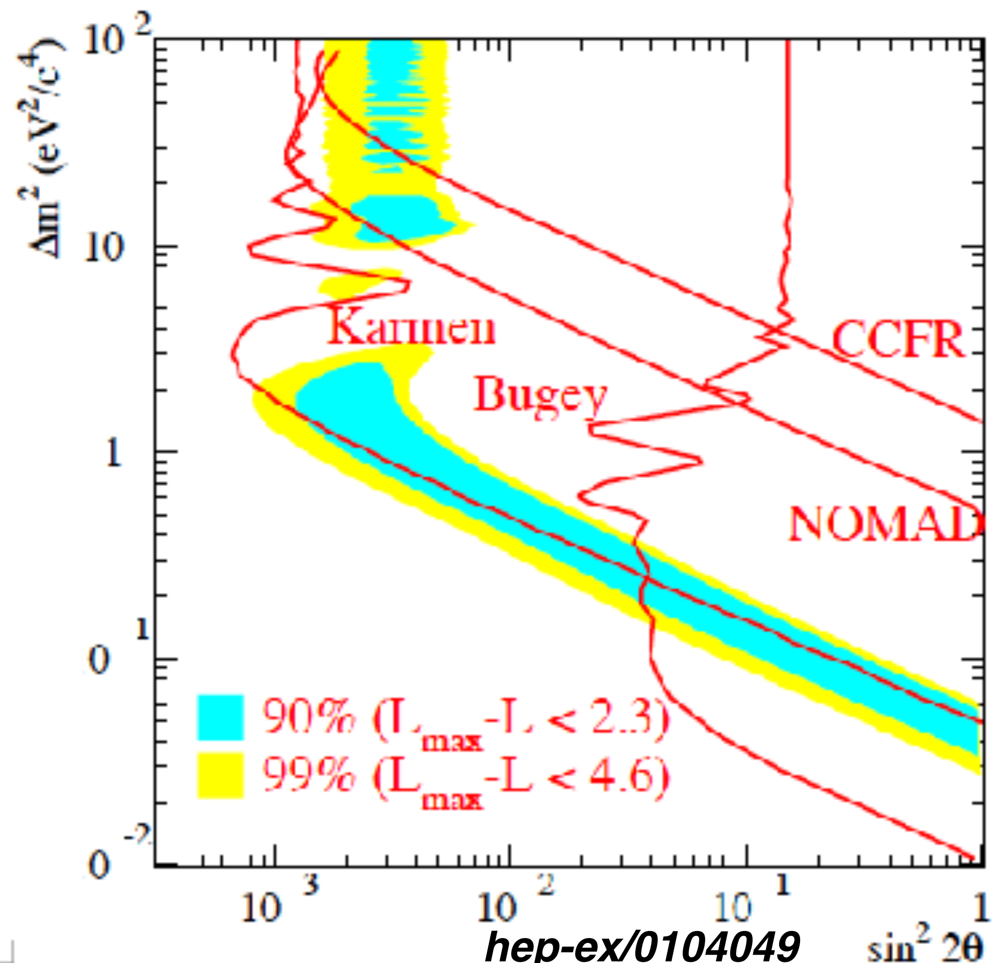
LSND versus KARMEN

KARMEN p-beam: ISIS in RAL, 800 MeV, 50 Hz, 100 ns double pulse separated by 325 ns

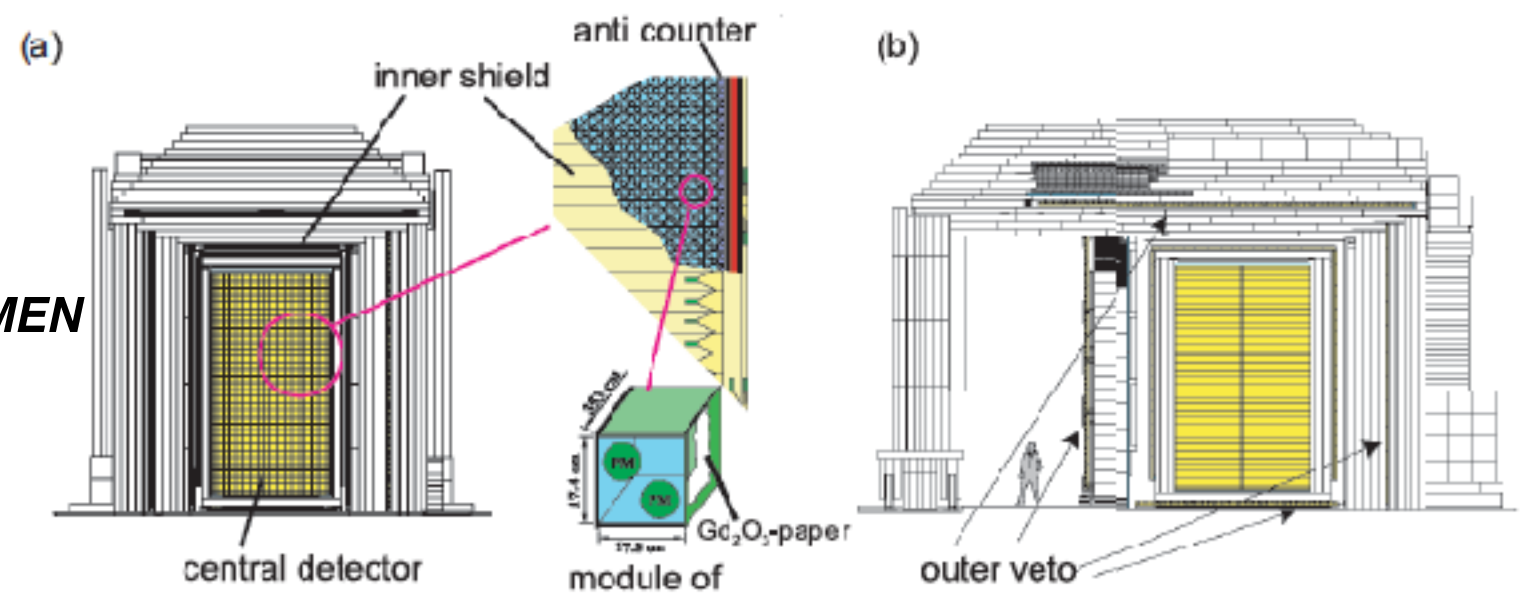
neutrinos: DAR from π and μ stops.

baseline: 17.7 m Phys. Rev. D65, 112001 (2002)

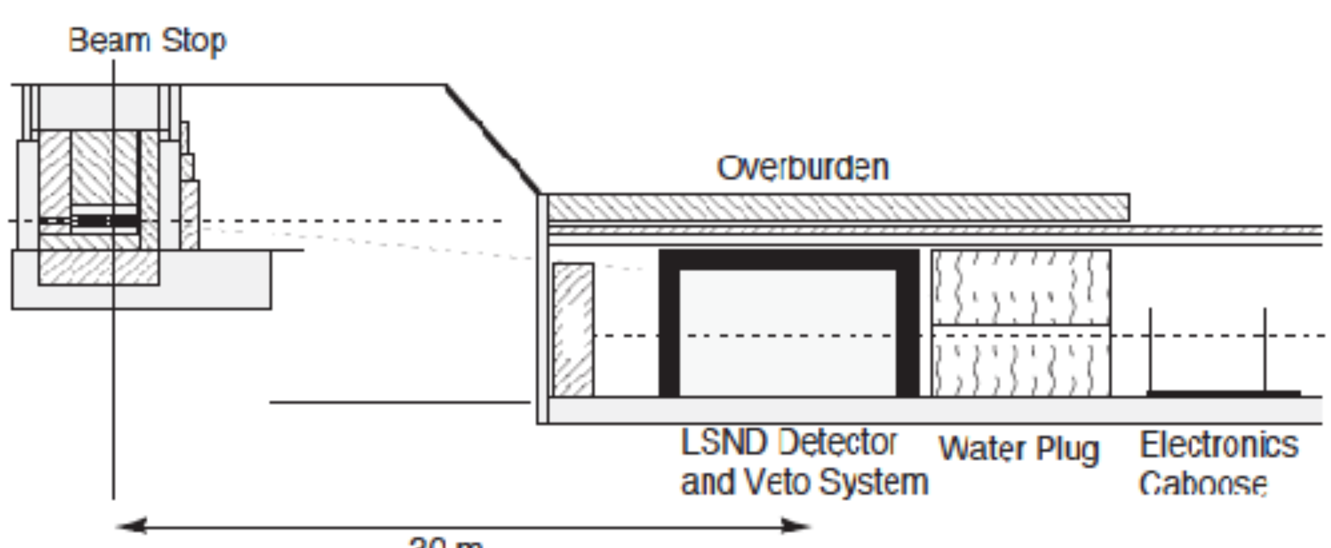
observation: 15 events with 15.8 expected bckg.



KARMEN



LSND



Key differences

beam duty factor
- ***LSND (continuous)***
- ***KARMEN (pulsed)***

neutron tag
- ***LSND (2.2 MeV γ in LS)***
- ***KARMEN (Gd ~8 MeV γ tag)***

Hint from MiniBooNE: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$

p beam: Booster in FNAL, 8 GeV
ν beam: π Decay-in-flight

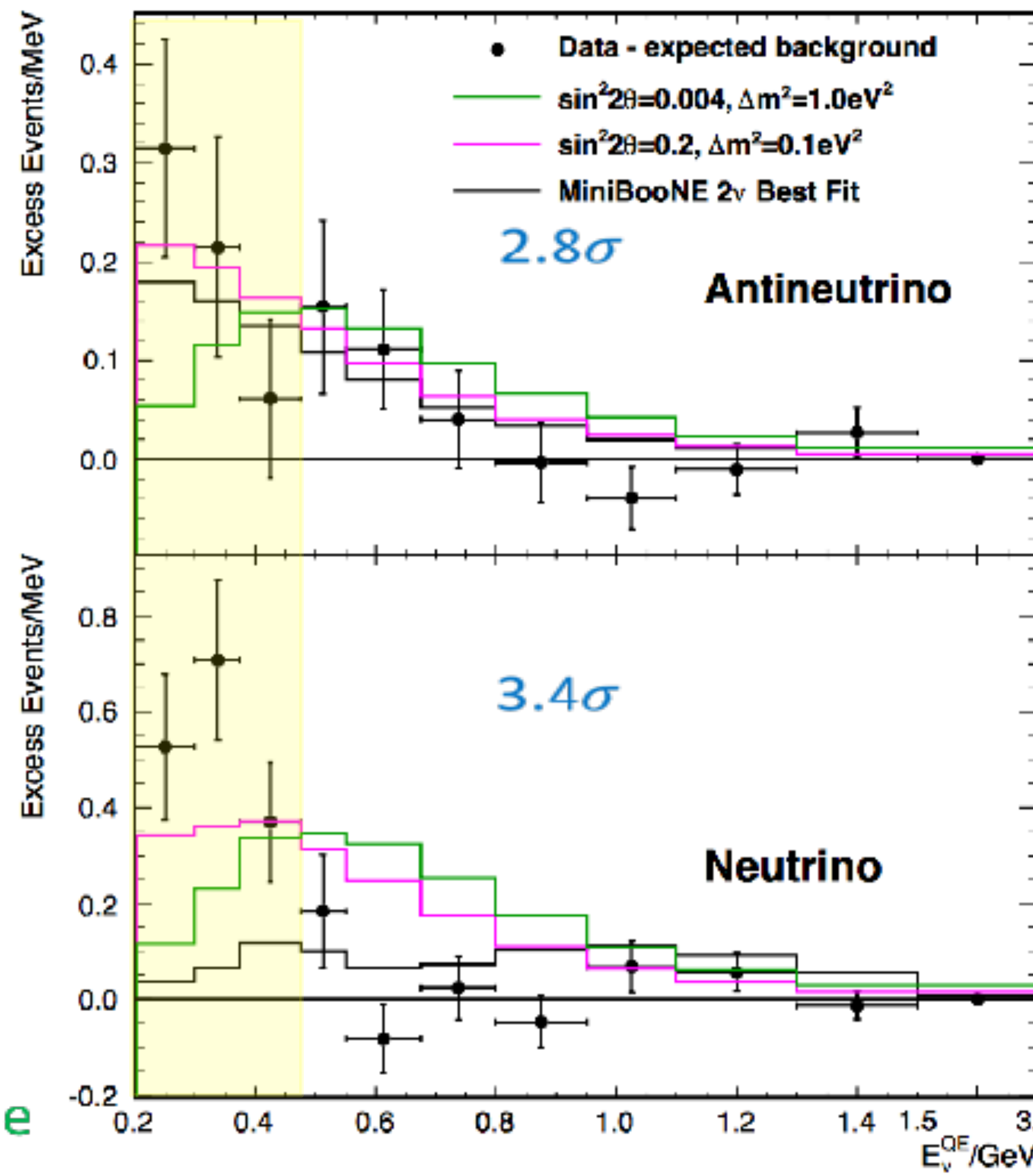
$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$

Oscillation modes: $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e$
Detection mode: $\nu_e + n \to e^- + p$
$\bar{\nu}_e + p \to e^+ + n$
Baseline: 500 m
Peak Energy: 600 / 400 MeV
L/E : ~ 1 m / MeV

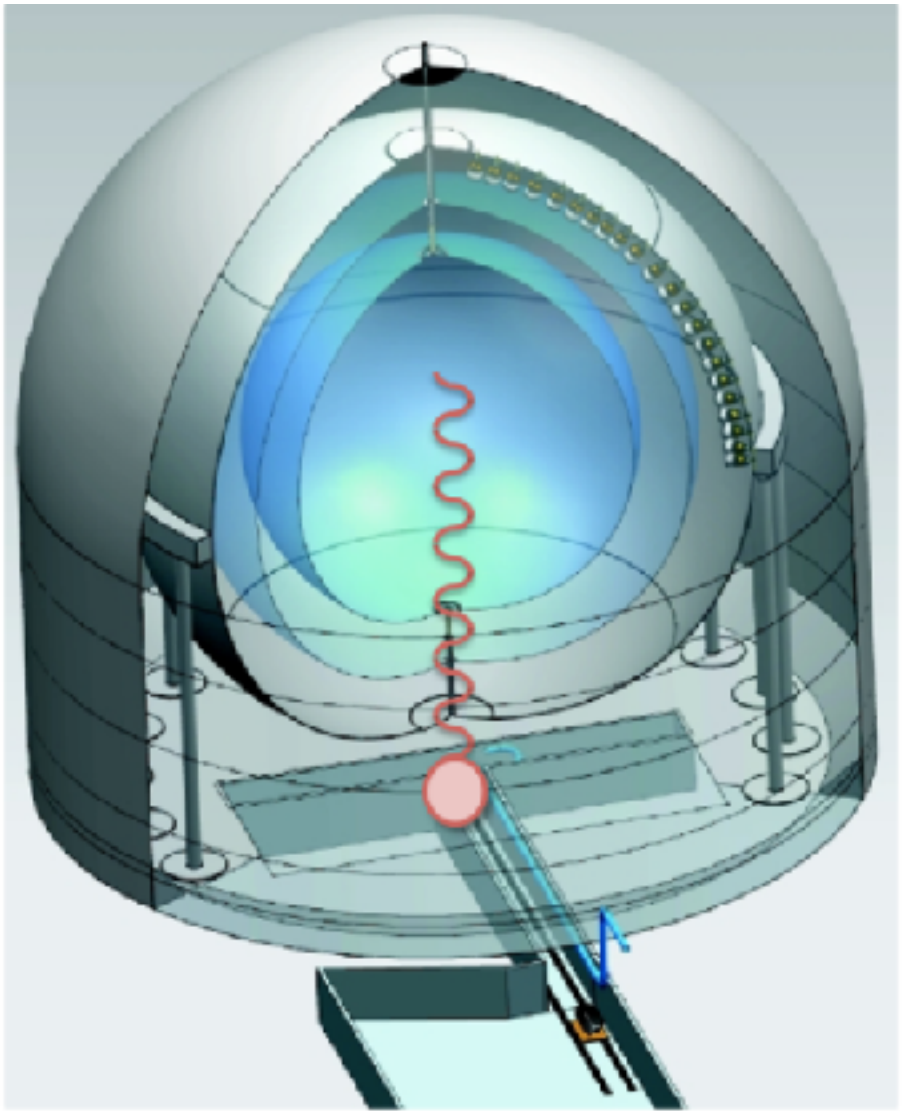
Event excess:
ν mode - 162.0 $\pm$ 47.8 (3.4σ)
$\bar{\nu}$ mode - 78.4 $\pm$ 28.5 (2.8σ)

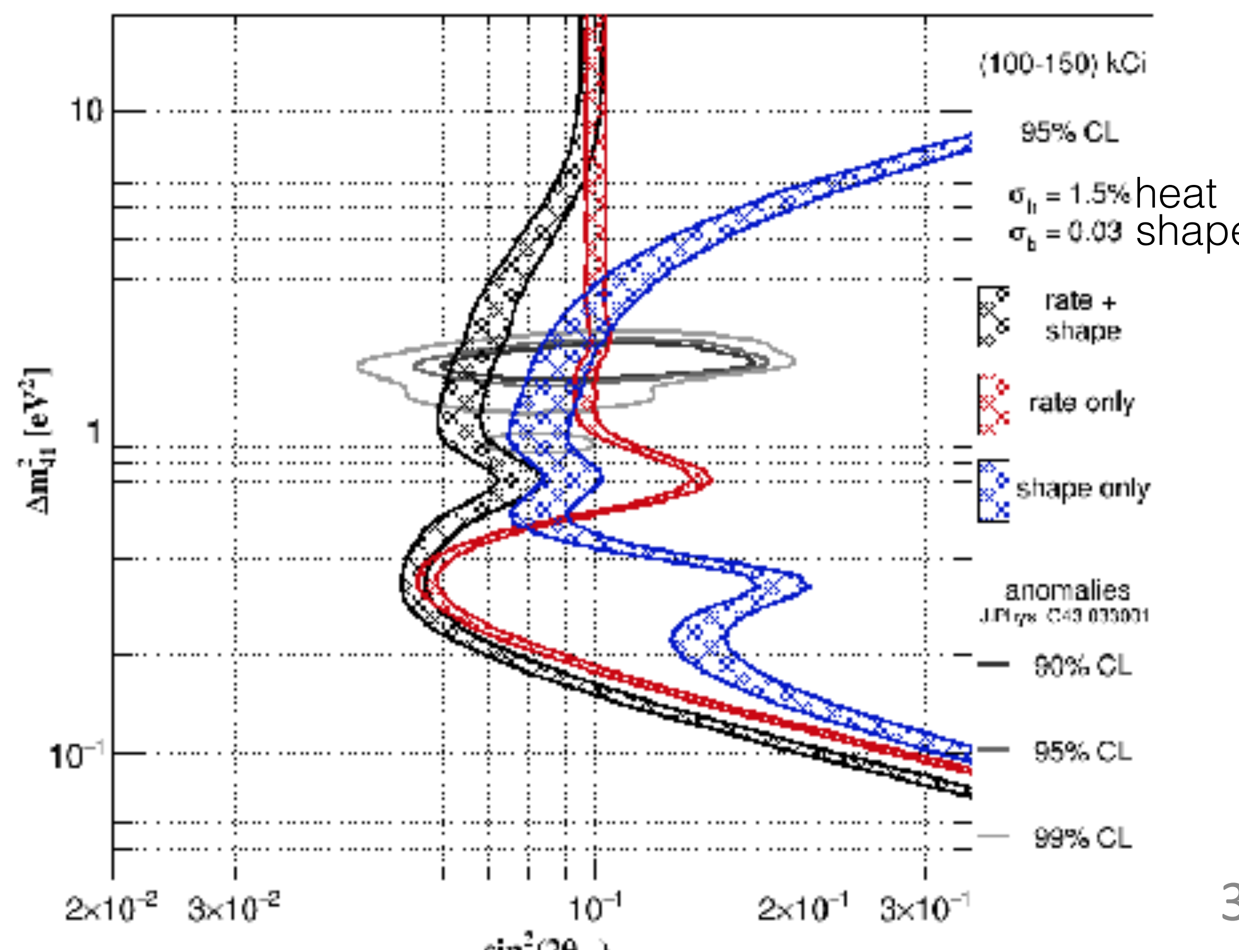
Above 475 MeV, no event excess for ν mode

Phys. Rev. Lett.110, 161801 (2013)



The SOX Experiment



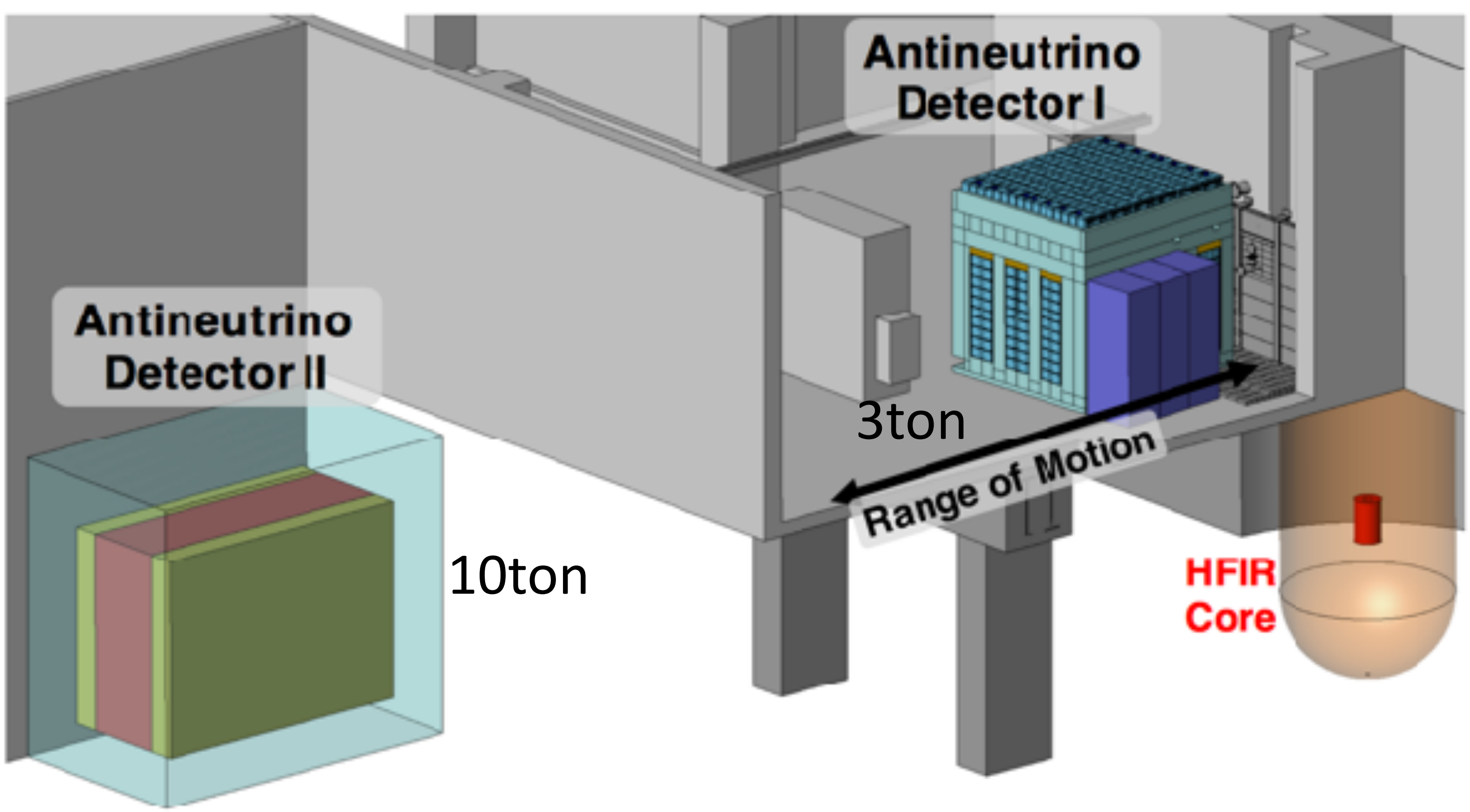


- 100-150 kCi ^{144}Ce $\bar{\nu}_e$ source (calorimeter)
- Baseline: 8.5 m from center
- 270 ton LS of Borexino in LNGS (3800 m.w.e.
- Rate+Shape measurement
- Data taking starts 2017-2018

Considerations: systematics due to spectrum and the heat measurement of the source.

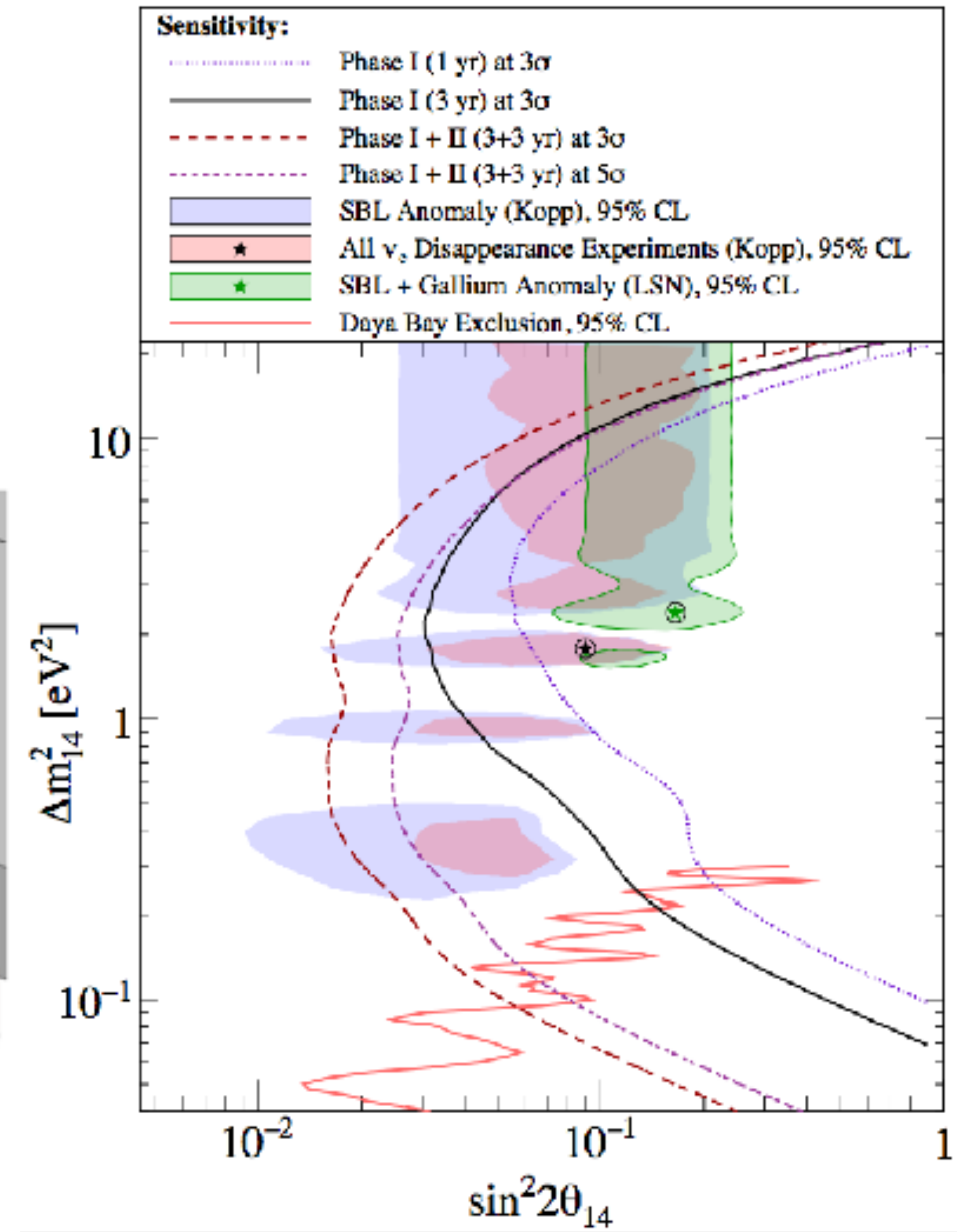
The PROSPECT Experiment (near future)

- 85MW ^{235}U HEU HFIR in ORNL
  - Core size: 0.38 m (Φ), 0.61m (H)
- Baseline: 6-12 m (AD1), 15-19 m (AD2)
- ^{6}Li-LS, segmented, PSD
- Phase R&D in progress and AD1 will be ready in 2017



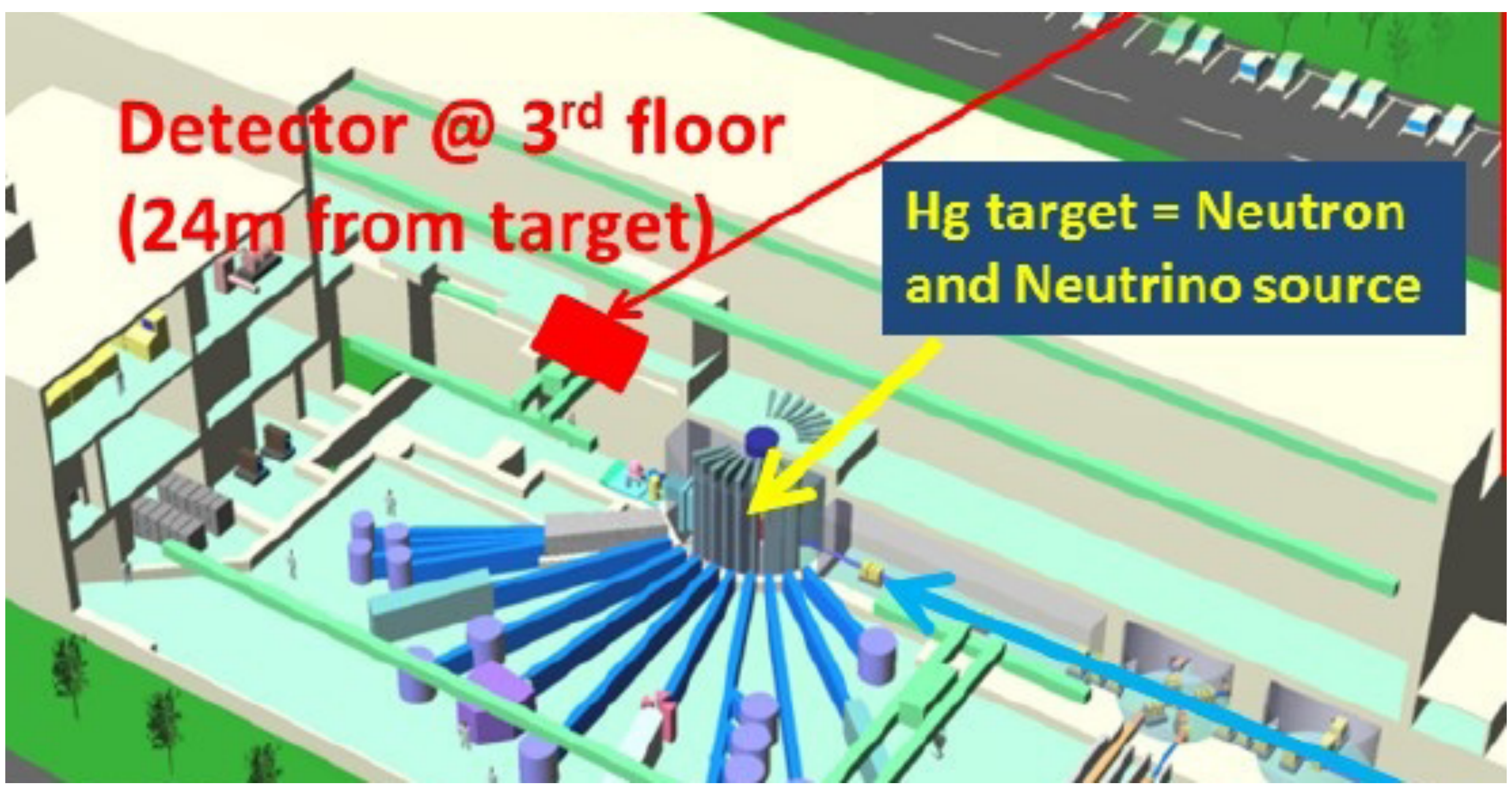
Talk: James Matta

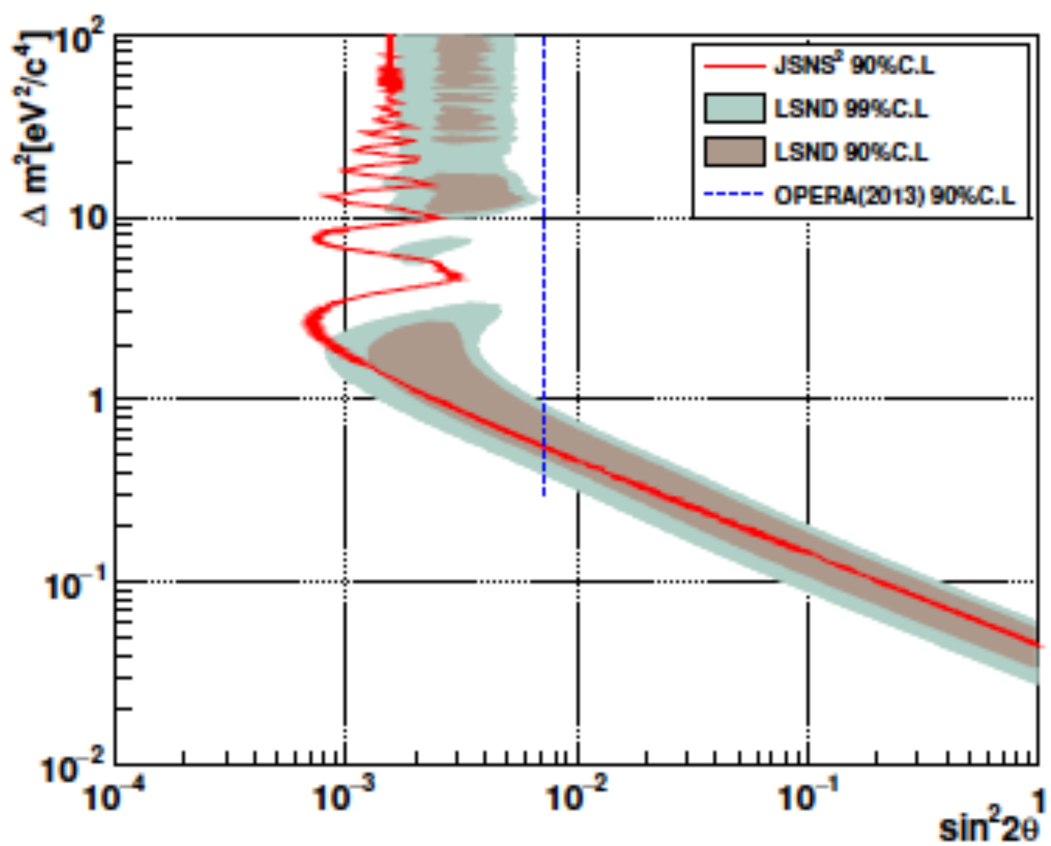
arXiv: 1512.02202



JSNS² / J-PARC E56 in Japan

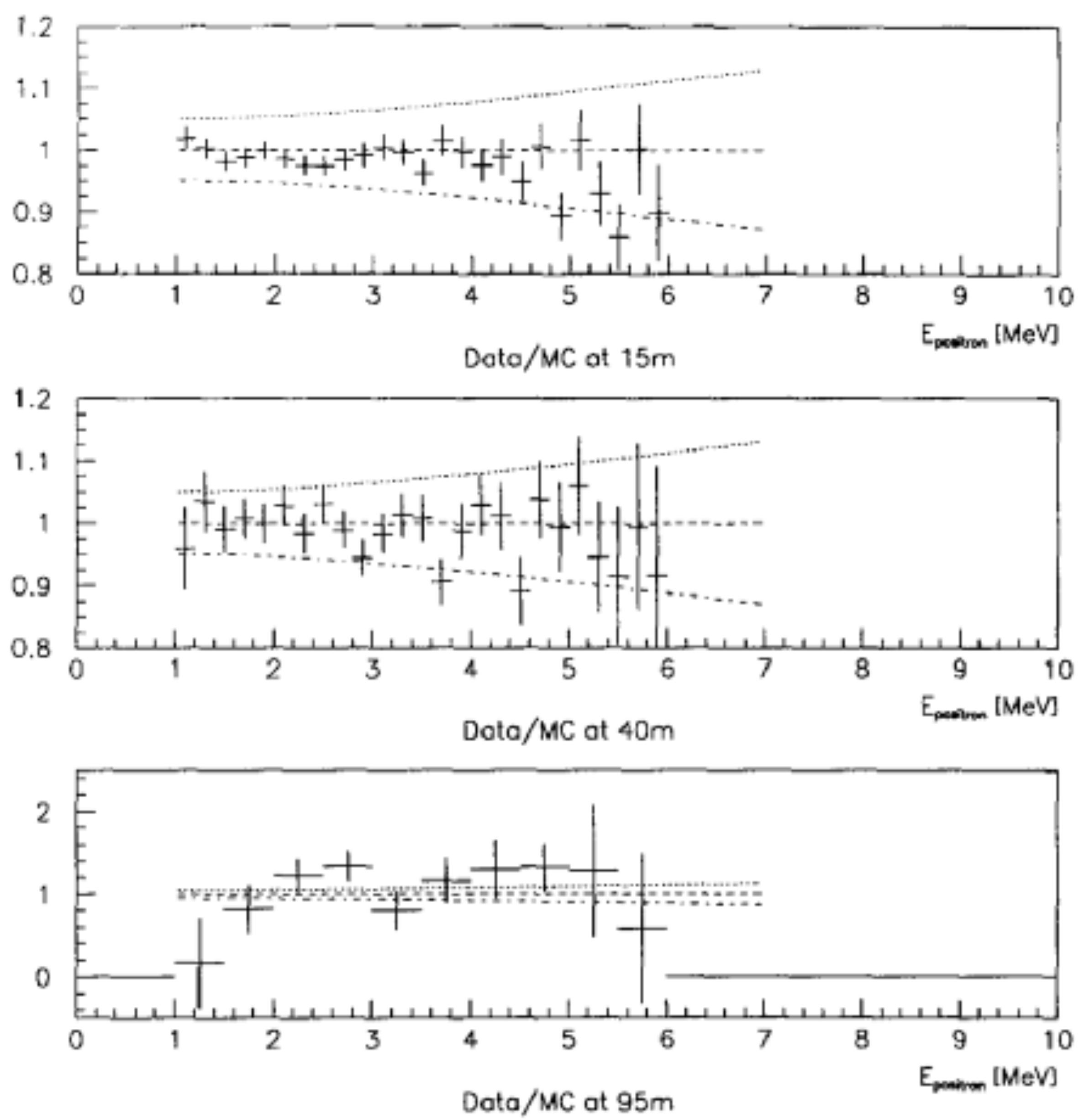
- Technical Design Report   1705.08629, May 2017
- Direct test on LSND anomaly with the same signal (start JFY2018)
- p-beam: J-PARC spallation neutron source. 1 MW 3 GeV
- pulsed beam: 25 Hz,   double pulse 100 ns separated by 540 ns
- Neutrino beam: pion and muon DAR (also includes ~1% flux from Kaon-DAR)
- GD loaded LS detector. Fid mass: 17 ton at baseline 24 m
- The JLF facility has constraints on placement of detector.
- 5000 hrs/yr X 3 yrs of exposure.



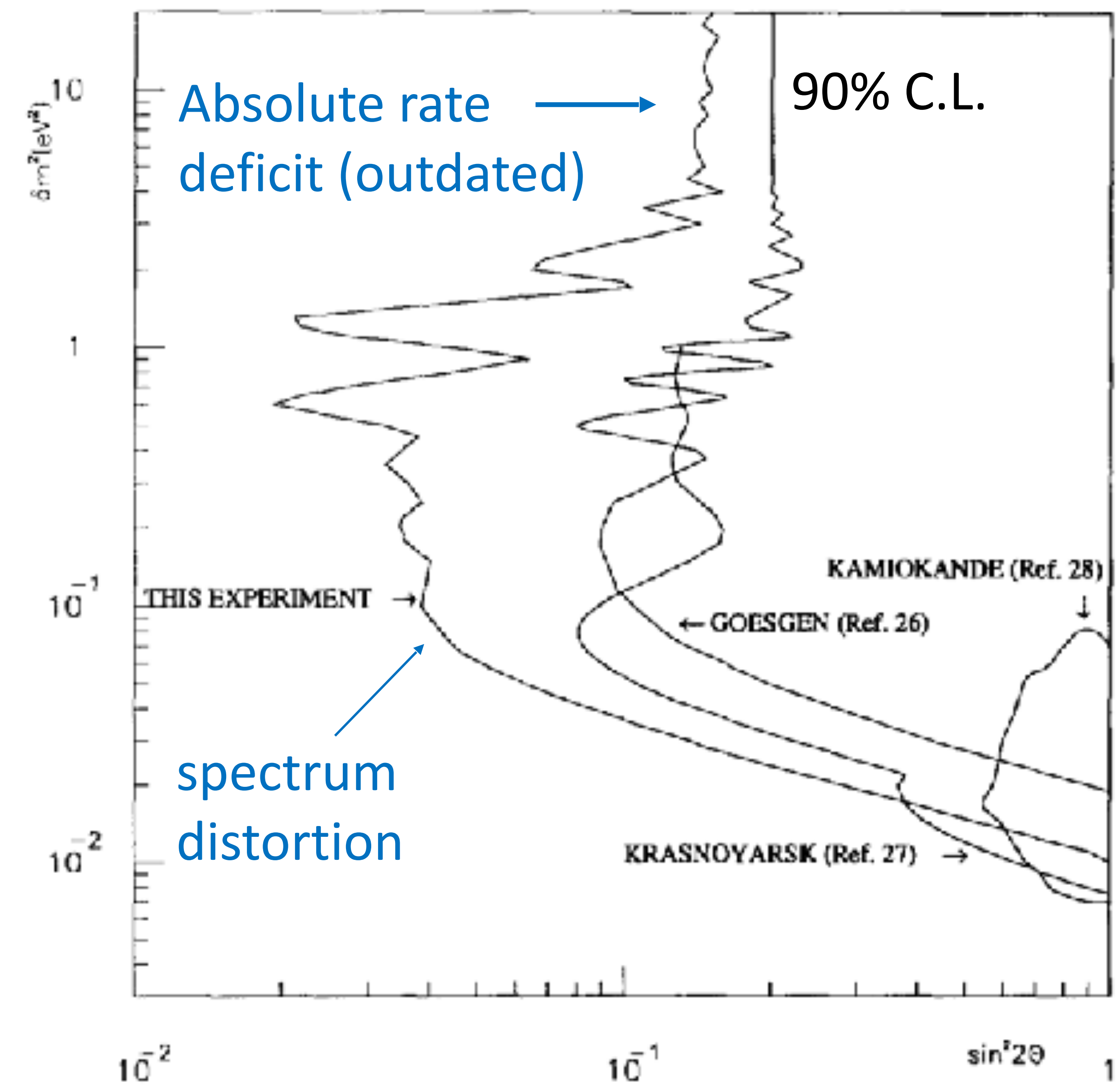


$\bar{\nu}_e \to \bar{\nu}_e$ from Bugey-3

- Bugey, France, PWR, 2.8 x 4 GW
- ^{6}Li-LS, segmented
- Baselines: 15, 40 and 95 m



Nucl. Phys. B 434, 503 (1995)



Disfavor sub-eV^2 oscillation

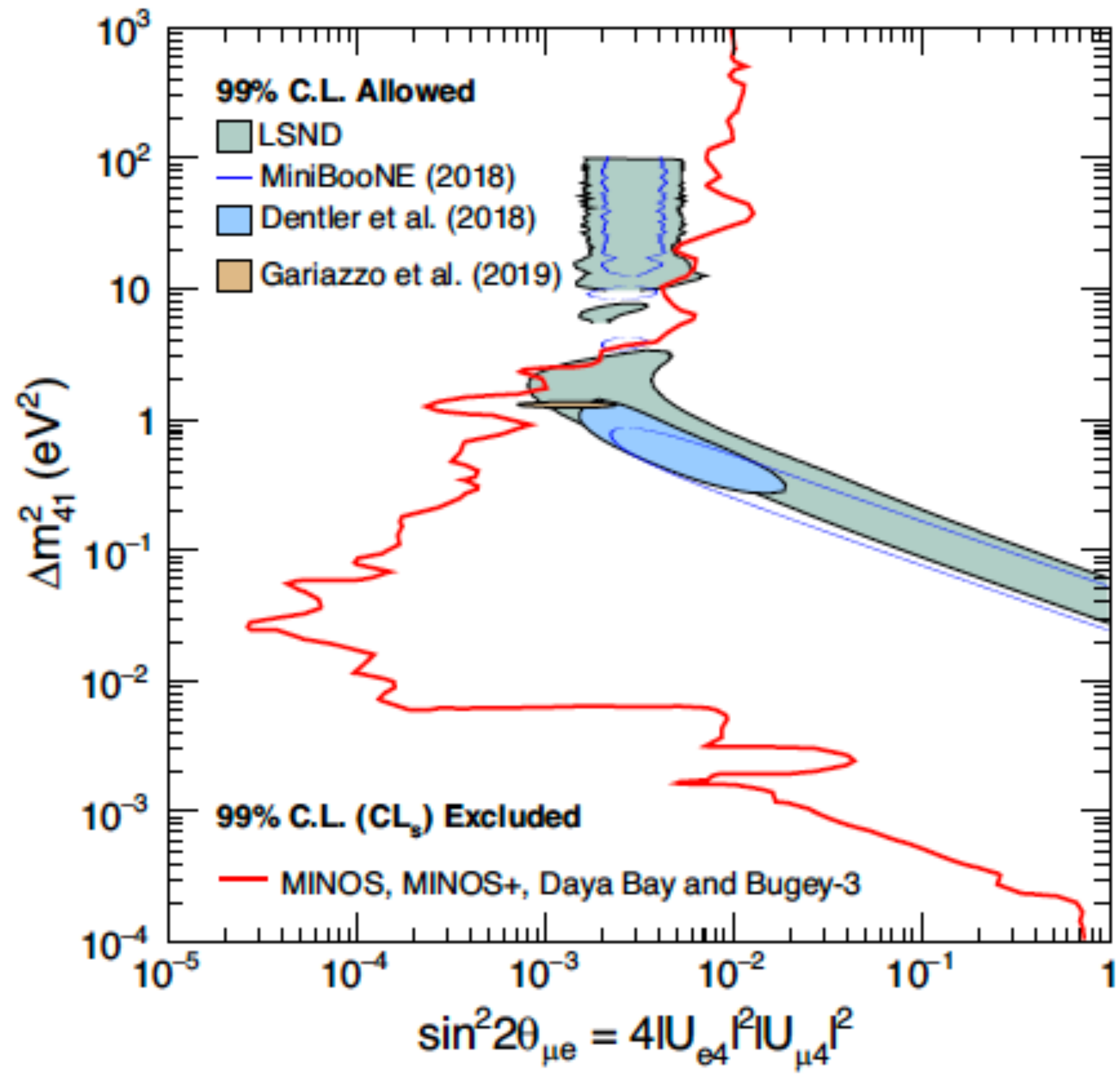


FIG. 4. Comparison of the MINOS, MINOSfl, Daya Bay, and Bugey-3 combined 99% CLs limit on sin2 2θμe to the LSND and MiniBooNE 99% C.L. allowed regions. The limit also excludes the 99% C.L. region allowed by a fit to global data by Gariazzo et al. where MINOS, MINOSfl, Daya Bay, and Bugey-3 are not included [57,58], and the 99% C.L. region allowed by a fit to all available appearance data by Dentler et al. [59] updated with the 2018 MiniBooNE appearance results [21].